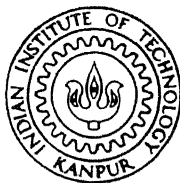# PREPARATION AND PROPERTIES OF NICKEL CLAD IRON/STEEL STRIP BY A POWDER METALLURGY ROUTE

By

B. N. SINGH

DEPARTMENT OF METALLURGICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

OCTOBER, 1985

PREPARATION AND PROPERTIES OF NICKEL CLAD IRON/STEEL STRIP BY A POWDER METALLURGY ROUTE

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of

MASTER OF TECHNOLOGY
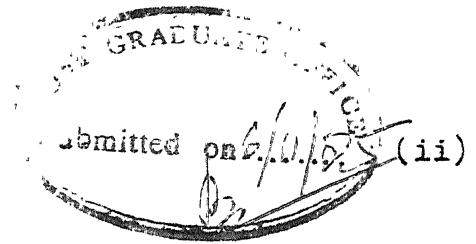
By

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to the

DEPARTMENT OF METALLURGICAL ENGINEERING

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OCTOBER, 1985

ME-1985-M-SIN-PRE

CERTIFICATE

This is to certify that the present work "Preparation and Properties of Nickel Clad Iron/Steel Strip by a Powder Metallurgy Route" has been carried out by Mr. B.N. Singh under my supervision and it has not been submitted elsewhere for a degree.

(R.K. DUBE)
Assistant Professor
Department of Metallurgical Engineering
Indian Institute of Technology, Kanpur

Dated : **October,** 1985.

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B.N. SINGH

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A Powder Metallurgy Route for making nickel clad iron/steel strip has been proposed, which consists of mixing separately iron/steel and nickel powder with a binder to form a homogeneous and free flowing slurry in each case. Iron/steel slurry is deposited into a strip form, and dried. Subsequently nickel slurry is deposited onto the dried "green" iron/steel strip, and dried to form a porous "green" Fe-Ni clad strip, which is then sintered at a suitable temperature followed by hot rolling in a single pass to produce fully dense clad strip. It is then cold rolled and annealed to produce finished Fe-Ni clad strip.

Hot and cold rolling reduction necessary for producing Fe-Ni clad strip have been established. It has been observed that in the initial stages of hot rolling of porous sintered Fe-Ni clad strip, there is no lengthening of the individual powder particles, which it occurs in the later stages of hot rolling. It has been possible to produce a cold rolled and annealed Fe-Ni clad strip having a tensile strength of 277 MN/m^2 coupled with an elongation of 39% by the above proposed Powder Metallurgy Route.

CLAD STRIP . ITS PROPERTIES, APPLICATIONS AND MANUFACTURING METHODS

1.1.1 Introduction

A clad strip consists of two or more layers or laminae of different metals metallurgically bonded to each other so as to yield a composite material whose properties differ from and are more desirable than those of its constituents. Such strips are also known as laminated metal composites. It usually consists of an abundant base metal, relatively inexpensive, with a second metal bonded to one or both of the surfaces of the base metal which is much more costly and scarce than the base metal.

Usually there is a confusion between two nomenclatures, viz. clad strip and coated strip. As a practice if the thickness of the material to be deposited is less than 25 μm, the strip is considered to be a coated strip. If the thickness of the deposited layer is more than 25 μm, the composite is considered to be a clad strip.

The metal that forms the cladding layer possesses certain desirable properties; some of which can be as follows :
(a) Corrosion resistance
(b) Wear resistance
(c) Electrical conductivity
(d) Improved magnetic properties
(e) Better appearance
(f) Thermal expansion

1.2 Properties of Clad Strips

The use of metal laminate in any engineering application is advantageous only if it offers improvement in some property or combination of properties at a cost lower than that of a monolithic structure. Properties to be considered in the selection and utilization of metal laminates are as follows :

    (a) Elasticity

    (b) Yield strength and plasticity

    (c) Fracture toughness

    (d) Electrical conductivity

    (e) Thermal conductivity

    (f) Thermal flexivity

    (g) Corrosion and erosion resistance

1.2.1 Elasticity

The effective elastic modulus or specific stiffness (stiffness to density ratio) of a metal laminate depends not only on the elastic moduli, density, and volume fraction of the individual metal comprising the laminate but also on their arrangement and the manner of loading of the laminated structure.

The elastic behavior of a laminated metal composite under uniaxial loading within the plane of the composite i.e. in any direction parallel to the laminae, is analogous to that of a

uniaxial fiber-reinforced composite. stressed parallel
to the fiber direction, and can be readily predicted on a
rule of mixture basis. Thus the effective Young's modulus of
a laminar composite is given by

$$E = E_1 f_1 + E_2 f_2 + \text{------------} + E_n f_n$$

E_1, E_2 ------ E_n are the Young's moduli and f_1, f_2 ----- f_n
are the volume fraction of the component materials.

Similarly, stiffness under bending loading within the
plane of the composite can be calculated by rule-of mixtures
equations.

In transverse bending or torsional loading, however,
rule of mixtures behavior is approximated for multiple layered
composites only if there is a large number of laminae and
the distribution of high and low-modulus materials is uniform
across the thickness of the composite.

In such a composite the stiffness of a rectangular beam
or plate composed of many alternate layers of thin laminae
of two materials, loaded as shown in fig. 1. 1 would be
similar to that of a homogeneous material.

$$M/(1/r) = EI = E\ bh^3/12$$

where,

    M = applied bending moment

    r = radius of curvature of the loaded beam
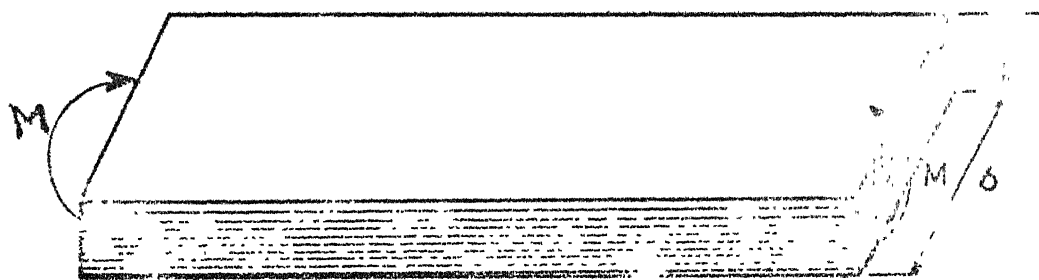
(a)

Fig. 1-1 Schematic diagram of (a) uniform laminates loaded in transverse bending.

b = base dimension of the beam

h = height of the beam

If the distribution of the two materials is not uniform throughout the cross section as shown in fig. 1.2.   The uniaxial rule-of-mixtures modulus cannot be used because stiffness in bending is determined predominantly by the outer layers, the contribution of each lamina being proportional to the square of its distance from the neutral axis. Stiffness of such beam is given by :

$$M/(1/r) = (b/6) \int Ex^2 dx$$

where, x is the distance from the neutral axis. If the thickness of the laminae are small in comparison with overall thickness of the composite, the stiffness of the laminate can be approximated by

$$M/(1/r) = (b/12) (E_1 t_1 x_1 + E_2 t_2 x_2 ----- + E_n t_n x_n)$$

where, E_1, E_2 ---- E_n are Young's modulus of the individual laminae, t_1, t_2, ----- t_n are their thickness, and x_1, x_2 ----- x_n their distance from the neutral axis. Thus a small amount of high-modulus material can be applied to the outer surface of a low-modulus core to produce a laminate having relatively high stiffness in the bending mode.

(b)
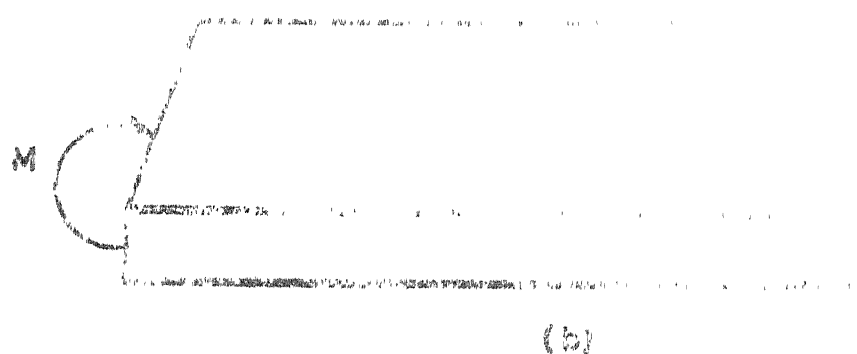
Fig. 1-1 Circuit diagram of nonuniform in transverse bending.

1.2.2   Yield Strength and Plasticity

Yielding under uniaxial tension occurs in one of the components of a laminated composite when the stress in that component exceeds its yield strength.   It is more convenient to consider a critical yield strain criterion given by

$$\epsilon_{y1} = \sigma_{y1}/E_1$$

Where, $_{y1}$ and E_1 represent the yield strength and Young's modulus of the particular component of the laminate. Thus, yielding of a laminate occurs when the strain in the laminate exceeds the yield strain of any of the component laminae. Thus, the criterion for yielding is

$$\epsilon_{c} > \epsilon_{y1}, \quad \epsilon_{y2} \text{ ---- or } \epsilon_{yn}.$$

or

$$\sigma_{c}/E_{c} > \sigma_{y1}/E_1 \text{ -- or } \sigma_{yn}/E_n$$

The predicted yield strength of a composite laminate is given by

$$\sigma_{yc} = \sigma_{y} E_{c}/E = (\sigma_{y}/E) (E_1 f_1 + E_2 f_2 \text{ -- } E_n f_n)$$

where, $_{y}$ and E are the yield strength and Young's modulus of the component laminate having the lowest σ_{y}/E ratio. On the basis of the rule of mixtures using an equal-strain hypothesis, Hawkins and Wright [1] found that the plastic behavior could also be predicted up to the point of plastic instability or necking in one of the component. The laminates

follows the classical work hardening equation :

$$\sigma = K\epsilon^n$$

K and n could be synthesized either graphically from the stress-strain curves of the components using the rule-of mixtures approach or analytically from their individual work hardening equations using the relationships

$$K = K_{Fe} t_{Fe} + K_{Ni} t_{Ni}.$$

$$n = \log (\sigma_{Fe} t_{Fe} \sigma_{Ni} t_{Ni}) - \log (K_{Fe} t_{Fe} + K_{Ni} t_{Ni}).$$

1.2.3 Fracture Toughness

A number of experimental studies have demonstrated that metal laminates having bond strengths or intermediate layers weaker than the major constituents of the composite possess better resistance to crack propagation than a monolithic material or strongly bonded laminate.[2] Two principal mechanisms were identified by Embury [3]. In a crack-arrester configuration in which the crack-propagation direction is perpendicular to the laminae, improved fracture resistance is attributed to delamination at an interface ahead of the propagating crack and consequent blunting of the crack and relief of the triaxial tensile stress state at its tip. Further propagation of fracture requires reinitiation of the crack, which absorb considerably more energy than continued propagation of an existing crack. In many cases reinitiation does not occur,

because further deformation of the laminate is accommodated
by plastic flow rather than fracture. In crack-divider
laminates the improvement in resistance to crack propagation
is also attributed to delamination ahead of the crack tip,
but the proposed mechanism is simply one of dividing the
laminate into a number of thin layers in the vicinity of the
crack tip, thus relieving the third dimensional plastic
constraint. Since yielding depends upon exceeding a critical
shear stress rather than a critical maximum tensile stress,
relief of the tensile stress in the third direction lowers
the principal tensile stress required to produce yielding,
thus encouraging plastic flow in lieu of cleavage.

Embury et al[3] demonstrated the striking decrease
in ductile-brittle transition temperature that can be achieved
in mild steel by the incorporation of a single crack-arresting
laminar of soft solder or copper (fig. 1.2. and 1.3.).
Their result also shows that the ductile-brittle transition
temperature of mild-steel crack-divider laminates decreases
gradually with decreasing thickness of the individual steel
laminae (fig. 1.4.'). Leichter[4] showed that increase in
charpy fracture energy up to 100% could be obtained in brazed
crack-divider laminates of maraging steel and Ti-5 Al-2.5 Sn
alloy. Almond et al[5] studied the fracture behaviour of
solid-wall and laminated-wall pressurized steel cylinders
containing through-wall simulated cracks. It was found that
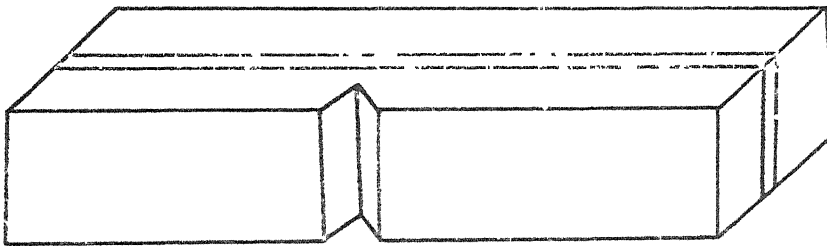
Fig·1·2 Schematic diagram of crack-arrester .
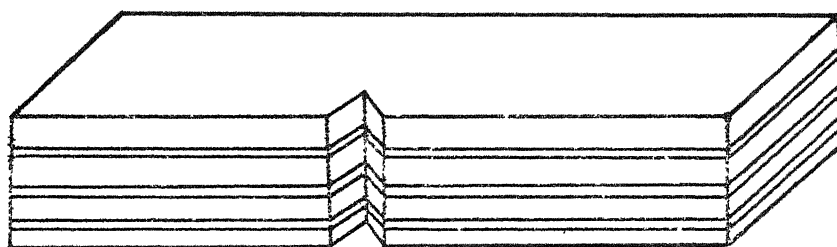
Fig. 1.3 Schematic diagram of crack-divider laminates .
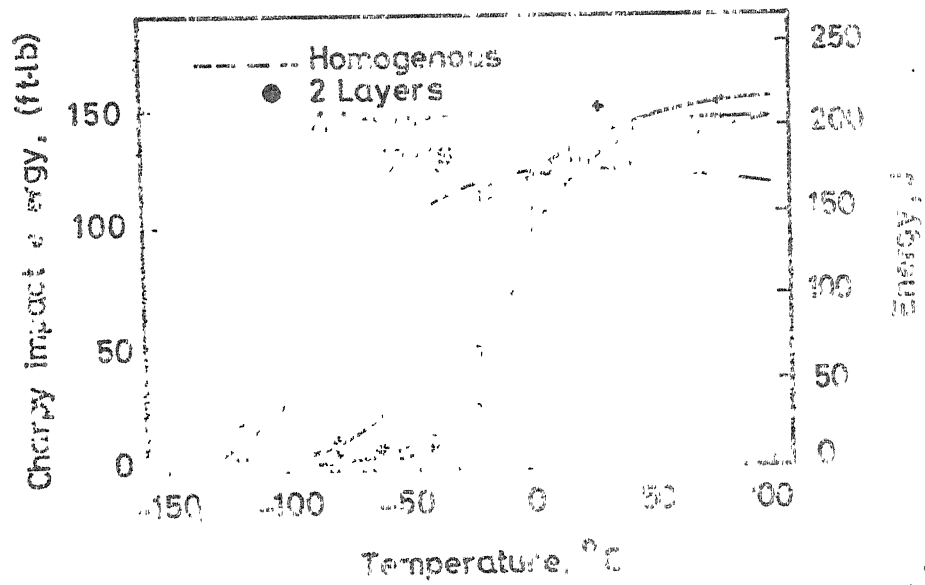
Fig. 1.4   Charpy impact en... ys. temperature for
homogeneous mild steel and silver ......
steel crack-divider laminates .

the solid-wall vessels failed in a brittle manner at all
temperatures below -5°C, with crack-branching and fragmentation
below -68°C, while the laminated vessels showed stable crack
growth and ductile behaviour at -75°C and above. It is thus
readily apparent that lamination can be used as an effective
means of controlling fracture toughness and avoiding catastrophic
brittle fractures.

1.2.4 Electrical Conductivity

Metal laminates are frequently used for applications
such as corrosion resistant wire and cable, heating elements
switch-contact springs, and circuit-breaker thermoelements; all
of which involve the conduction of electricity. In clad
wire or strip or in laminar composites in which the conduction
direction is parallel to the laminae, the conductivity of the
laminate can be readily calculated on the rule-of-mixtures
basis in which

$$K_c = K_1 f_1 + K_2 f_2 + \cdots + K_n f_n$$

where,

K_c is the conductivity of the composite, K_1, K_2, K_2 ---- K_n
are the conductivities of the individual components, and f_1, f_2 --f_n
are their respective volume fractions.

Since the resistivity is the reciprocal of the conductivity,
the effective resistivity of a metal laminate parallel to
the laminae is given by

$$\frac{1}{R_c} = \frac{f_1}{R_1} + \frac{f_2}{R_2} + \text{------} \frac{f_n}{R_n}$$

where,

R_1, R_2 ------ R_n are the resistivities of the component laminae.

1.2.5 Thermal Conductivity

A major usage of metal laminates is for applications in which improved heat flow is desired in directions parallel to the sheet surface, even though the surface layers must be made of materials of low thermal conductivity because of corrosion or wear resistance, strength or other considerations.

By incorporating layers of high-conductivity materials within the laminate high conductivity in directions parallel to the sheet surface can be achieved. Typical applications are cooking utensils, laboratoryware, heat exchangers and chemical process vessels.

The thermal conduction in laminates parallel to the laminae are similar to the electrical conductivity.

$$K_c = K_1 f_1 + K_2 f_2 + \text{------} K_n f_n$$

where K_1, K_2 ------ K_n are the thermal conductivities of the component laminae, and f_1, f_2 ----- f_n are the respective volume fraction of the component laminae.

In some applications such as heat exchangers, thermal conduction perpendicular to the surface is of paramount importance. Thermal conductivity in this direction is given by

$$\frac{1}{K_c} = \frac{f_1}{K_1} + \frac{f_2}{K_2} + \text{------} \frac{f_n}{K_n}$$

provided there is a perfect thermal bond between layers and there are no low-conductivity layers that have formed by surface contamination or intermetallic diffusion. Such layers would obviously decrease thermal conductivity and would need to be accounted for by the addition of appropriate terms to the conductivity equation.

1.2.6 Thermal Flexivity

The basic quantity used to describe the thermal activity or sensitivity of thermostat elements is flexivity, defined by an ASTM standard as "the change in curvature of the longitudinal centerline of the specimen per unit temperature change for unit thickness".

$$F = \frac{(1/R_2 - 1/R_1)t}{T_2 - T_1}$$

where, $\frac{1}{R_1}$ and $\frac{1}{R_2}$ are the curvatures at temperatures T_1 and T_2 respectively, and t is the total thickness of the element. Flexivity, in turn, depends upon a number of material properties and geometrical factors. The change in curvature of a two layers laminate with change in temperature can be

calculated by means of an equation developed by Timoshenko[8]

$$\frac{1}{R_2} - \frac{1}{R_1} = \frac{6(X_2-X_1)\ (T_2-T_1)\ (1+m)^2}{h\ [3(1+m)^2 + (1+mn)\ (m^2+1/mn)]}$$

where, $m = t_1/t_2$, the thickness ratio

$n = E_1/E_2$, the elastic moduli ratio

X_1, X_2 = linear expansion coefficients

T_1, T_2 = initial and final temperatures

$\frac{1}{R_1}$, $\frac{1}{R_2}$ = initial and final curvatures

1.2.7 Corrosion and Erosion Resistance

The resistance to corrosion, erosion or wear is largely
determined by the properties of the surface layers. Exception
to this rule occurs because of galvanic corrosion reactions
between the cladding and the exposed core if unprotected edges,
holes. or cladding defects are exposed to the corroding medium.
This can seriously reduce the observed corrosion resistance of
the surface of the composite in the vicinity of the exposed
edge, or it can cause rapid corrosion of the core and apparent
delamination of the composite. If the surface layers of
the composite are strongly anodic with respect to the interior
layers, the surface may corrode sacrificially, leaving the
core material cathodically protected against corrosion even
when it might otherwise be highly susceptible.

1.3 Applications

The following examples illustrate the advantageous application of clad strips.

1.3.1 Chemical Process Equipment

Titanium is one of the most widely accepted metal for constructing chemical process equipment due to its superior corrosion resistance, erosion resistance, and antifouling properties. However, the use of solid titanium pressure vessels is seriously limited by their prohibitively high cost of two to four times that of the equivalent stainless steel. The advent of titanium clad steel has greatly broadened the use of this metal in chemical process equipment because of cost saving. The inner titanium layer provides the desired corrosion resistance, while the outer layer of the steel provides the needed strength.[6] Lead also possesses high resistance to corrosion. The high corrosion resistance of lead added to the inherent strength of steel has also been used to advantage in chemical industry. Lead clad steel has been used in the construction of tanks for strong acids and other corrosive liquids.[7]

1.3.2 Structural applications .

The most desirable requirements for aircraft structures and skins are that they must be strong, light weight, corrosion resistant and fatigue resistant. These favourable properties

are embodied in clad aluminium strip. The core alloy provides
the desired mechanical properties while the clad layer
provides long-term corrosion resistance. Such clad aluminium
sheet 0.032" thick, has been developed by ALCOA and marketed
under specification Alclad 2024-T3, which has 2024-T3 core
and 1110 aluminium cladding layer.[8]

The use of aluminium superstructure joined steel decking
is very attractive in marine applications. The aluminium structure
was mechanically joined to the steel. This type of joint
was very unsatisfactory because of severe galvanic corrosion.
The development of aluminium clad steel[9] offered a way
of circumventing this problem, by the use of an aluminium-
steel transition joint that would permit joining the aluminium
superstructure to the aluminium side of the joint and steel
decking to the steel side of the joint by conventional
welding technique.

1.3.3 Thermostats

Thermostats represent an extensive growing, and indis-
pensable application of clad strips. Basically, a thermostat
consists of bonded layers of two or more metals in the strip
or sheet form having different coefficient of expansion
such that the composite material undergoes a change in curva-
ture when its temperature is changed. High expansivity
components include brass, monel ,austenitic nickel-chromium-
iron and nickel-manganese-iron alloys, nickel-molybdenum iron

alloys, "' high manganese-nickel-copper alloys. These are bonded to low-expansivity components, which are usually of the Invar groups (Nickel-iron alloys,.[10]

1.3.4 Architectural and Building-Trade applications

Copper is being commonly used in architectural application, particularly in the West. Copper-clad stainless steel is an attractive alternative to monolithic copper. A typical such commercial clad strip consists of 10% of copper layer metallurgically bonded to both sides of an 80% core of type 404 stainless steel. Such material has been effectively and economically used in roofing as face sheets for wall pannels, flashings, rain drainage, window and door frames etc. Table 1.1 shows the superior mechanical properties of copper-clad stainless steel as compared to monolithic copper used in architectural applications. Lead has excellent properties of sound attenuation when weathered. The aesthetic appearance of lead, in addition to its ease of shaping and proven protective properties has made it a popular material with architects and in building industry. Its mechanical properties, however, have sometimes tended to limit the applications for which lead could be used. One method out of various methods developed to improve these properties is to use lead cladded steel in place of monolithic lead. Lead cladded steel is now used as permanent panelling material, effective roofing material and sound barrier material in architectural

Table 1.1

COMPARISON OF COPPER AND COPPER-CLAD STAINLESS STEEL

Property	Copper	Copper-clad stainless steel
Nominal temper	So ft.	Soft.
Standard thickness (in)	0.020	0.015
Relative cost (copper = 100)	100	75
Yield strength (1000 psi)	11	35
Tensile strength	35	63
Elongation	36	30
Wt./sq.ft.(lb)	1.000	0.628
Thermal expansion coefficient Mo^{-6} in/in-°F	9,8	6.1
Thermal conductivity $(Btu/hr\text{-}ft.^2\text{-}°F)$	226	37

applications.

1.3.5 Coinage

Clad strips were first introduced in the U.S.A. in 1965 to make coins. To-day most of the U.S. coins are made from metal laminates, consisting of a layer of copper sandwiched between two thinner layers of 75 Cu-25Ni alloy in the proportions by volume $\frac{1}{6} : \frac{2}{3} . \frac{1}{6}$ [11]. The outer layer of cupronickel alloy provides the required appearance, abrassion resistance and corrosion resistance, while the inner copper layer contributes to the required density.

1.3.6 Defence applications

Dual-hardness armor is another example of the use of clad sheet to achieve what cannot be done with monolithic metal. In this application a very-high hardness (RC-60) steel is metallurgically bonded to a tougher, more ductile and softer (RC-50) backing steel.[12] The very hard facing serves to break up the steel core of an armor-piercing projectile, while the tough backing holds the facing together and absorbs the deformation caused by the projectile impact without cracking. Dual hardness armor substantially reduces the weight required to defeat small-arms projectiles as compared to the standard rolled homogeneous steel armor.

Another interesting application of clad strip is in manufacturing bullet-jackets, which traditionally made from copper

alloy. Steel cladded with 90-10 brass as gilding metal has been proved to be a successful substitute for the traditional copper alloys used for making bullet jackets.[13] The ballistic performance of the laminated bullet is superior to that of its unclad counterpart, with a 72% saving in copper. A typical jacket consists of gilding metal-steel-gilding metal in the proportion by volume of 15:80:5. The inner layer of gilding metal is used to facilitate deep drawing the jacket.

1.3.7 Bearing Materials

Engineering developments in recent years have made increasingly severe demands on plain bearings. "Bimetal" and "trimetal" bearings are now widely employed in the U.S.A. A bimetal bearing is a bearing alloy on a backing which is generally steel. A trimetal bearing is a steel-backed bearing with an overlay; there are three different alloy layers. Steel cladded with Pb-Sn alloy or Pb-Sn-Cn etc. alloy is commonly used bimetal bearing material.[14]

1.4 Clad Strip Manufacturing Methods

Commercial clad strips are fabricated by a variety of techniques; the most common of which are as follows :

(a) Cast bonding

(b) Roll bonding

(c) Explosive welding

(d) Spray forming

(e) Powder metallurgy

1.4.1 Cast bonding

Premium quality metallic composites can be produced by cast bonding. The process is applicable when it is uneconomical or impossible to produce the composite by conventional processes. It is a controlled process for producing metallurgically joined composites by casting liquid metal. Bonds are as strong as the weaker of the two base materials.[15] Overall dimensional tolerances of composites produced in this way approach those for investment castings.

In this process, the back up metal is cleaned and preheated under nonoxidizing conditions. The preheat conditions are such that the temperature of the bonding of the back up metal slightly exceeds the solid temperature of the cast metal at the moment that the cast metal contacts the solid metals.

The preheat and pour temperatures are calculated to achieve instantaneous wetting and bonding. If the back up metal is preheated to too low temperature, bonding does not take place. If the back up metal is heated to a too high temperature, solution of the back up metal occurs. There, exact process control is required for success of cast bonding.

Some metal combinations that have been successfully cast bonded are shown below :

Cast metal	backup metal
Alloy iron	Carbon steels
Copper	Carbon steels
Cu-0.8 Cr	Core iron
Inconel X	AISI 4140 steel
Inconel 713LC	HP 9-4-20 steel
Inconel 718C	AISI 4340 steel
MAR-M-211	AISI 4340 steel

1.4.2 Roll bonding

Roll bonding is widely used in the fabrication of laminar composite. In this process the metals are bonded by rolling under heat and pressure so that an internal bond is formed over the entire interfacial area. Cladding thickness generally ranges from 2.5 to 20% of the total laminate thickness depending upon the application .

The combination of the uniform pressure produced by the rolling mill and high temperature of the pack serve to forge weld the components together into an integral metallurgically bonded composite.

Generally a four ply assembly is prepared which is composed of two base metal plates (backers) and two clad metal plates/ sheets. These components are assembled into a sandwich form, as shown below :

Welded spacer bar

Carbon steel backing

Parting compound

Stainless steel cladding
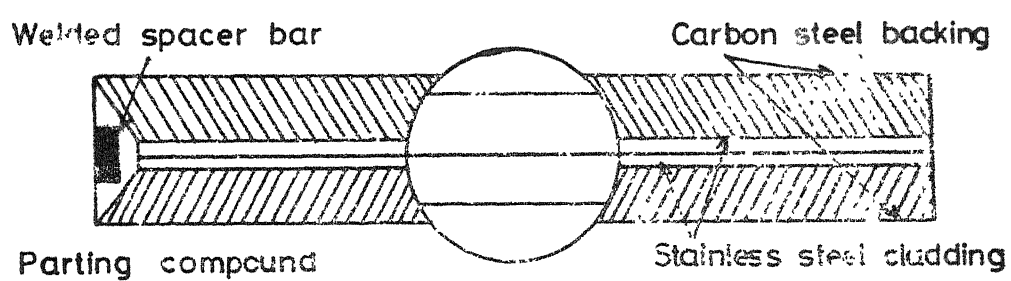
Fig: 1.5   Schematic cross section of the single-clad pack prior to rolling.

Base metal/clad metal/refractor parting layer/clad metal/
base metal

After being rolled into a plate, they will be pulled apart
forming two clad strips. The parting layer helps in preventing
any bond formation between the two clad strips. Before
assembling, the joining surfaces of the base metal and clad
metal plates are cleaned by sand blasting to remove any
mill scale. The entire assembly is then tack welded. The
clad assembly is heated to an appropriate temperature in
a suitable furnace. The heated assembly is rolled to the
required thickness. Finally the assembly is opened by
shearing or burning. Table 1..2 shows the feasibility
of the metal laminate produced by roll bonding. The success
of the roll bonding depends on the following factors.

1. Preheating temperature

2. Reduction in thickness

3. Rolling speed

4. Initial thickness of the cladding material.

The rolling temperature had a pronounced effect on the
bonding of metals. Below certain temperature bonding
does not occur and above certain temperature is no effect.
Table 1. 3 [16] shows the minimum rolling temperature required
for bonding to iron/steel.

The reduction in thickness during rolling was found to
have only a slight effect on the bond strength of metals joined

Table 1.2.

COMPOSITE METAL COMBINATION
BASE METAL

Cladding	Al.	Brass	Cu	Au	Pb	Mg.	Ni alloy	S.S.	Sn	Ti	Zn.	Fe
Al.	x	x	x	x		x	x	x	x	x	x	x
Brass	x		x									
Cu	x						x	x				x
Au	x	x	x				x	x				x
Pb	x	x	x				x					x
Mg												x
Ni	x	x	x							x	x	
Sn	x	x	x		x	x						x
Ti			x									
Zn	x											

x denotes fisible combination

Table 1.3

MINIMUM ROLLING TEMPERATURE REQUIRED FOR BONDING TO IRON

1.3 mm thick cladding 20% reduction in thickness 2×10^{-5} torr residual gas pressure.

Metal	Minimum bonding temp. °C	Bond shear strength MP.O.
Copper	1000	191
Chromium	900	105
Nickel	650	286
Monel	800	301
Inconel	900	-
304 SS	800	285
430 SS	800	291
Molybdenum	900	248
Mo -0.5 Ti	900	277
Cd-D-36 Alloy.	1100	275
Tantarlum	1000	230
Titanium (Ti-40)	800	288
Tungsten	1200	765
Zr. alloy-2	900	235

to iron. However, a certain minimum reduction is required
for successful bonding. In the case of Ti-Fe bimetal system
having thickness of iron and titanium as 1.8 mm and 0.10-0.18
mm respectively, a minimum of 7.5% thickness reduction was
needed to have effective bonding.[17] The rolling was done
under vacuum. Further reduction did not have any effect on
the bond strength.

Rolling speed is a superficial parameter that affects
bonding only because of its effect on time-temperature
history of the interface. At slower rolling speed the inter-
face is maintained under pressure between the rolls for
larger times. It also decreases the temperature. Diffusion
is much more dependent on temperature than time hence a lower
temperature results net decrease in diffusion. Some times
temperature falls below the temperature which is required for
bonding.

Thinner clads cool faster and therefore require higher
initial temperature or faster rolling speed or both.

Lead clad steel has been successfully produced. For
satisfactory bonding 50% reduction in lead was required.[18]
As the steel is not measurably deformed during the roll bonding
process, the mechanical properties of the composite are
virtually the same as those of the steel itself.

mild steel and low alloy steel can be successfully roll
cladded with stainless steel. The cladding alloys available
include 13% Cr, 18/8 and 18/8/2 stainless steel both low
carbon and stabilized types, Nickel, Monel, Inconel and
Incoloy. The backing steel can range from ordinary mild steel
to Mo and Cr/Mo creep resistant steel and include grain
refined with either Al or Nb.[19]

The difficulty with roll bonding is in keeping the
surfaces to be bonded sufficiently clean and free of oxides
to alloy metal-to-metal bonding. The difficulty can be minimised
by carrying out the entire operation an evacuated chamber.[20]
Reactive metals such as titanium, zirconium, chromium, and
columbium could be clad on steel without the occurrence of
excessive oxidation, if the pressure was kept below app
$5x10^{-5}$ torr. The less reactive metals such as iron, molybdenum,
and copper could be processed at 10^{-3} or 10^{-2} torr.

1.4.3   Explosive welding

Explosive welding or bonding is used to join a wide
range of both similar and dissimilar metals with a high-
integrity metallurgical bond. In explosive welding, a layer
of explosive is placed over one or both of the metal pieces
to be bonded and, upon detonation, the workpieces are
accelerated towards each other. The detonation front proceeds
across the surface of the accelerating flyer plate, causing
part of the plate behind the front to accelerate, while the
undisturbed part remains stationary. The plate thus becomes

deformed and, as shown in fig. 1.6   acquires a dynamic
bend angle   and a plate velocity   . At the collision poi t
of the two pieces, impact occurs at a dynamic collision
angle   . A section normal to the interface in any bonding
operation would exhibit one of the relative plate geometries
shown in fig. 1.7.

The main advantage of this method is that it is not
limited by large differences in melting point or plastic
properties of the metal to be joined. The explos ve clad
strip can be hot or cold rolled to the required thickness
level. In parallel-plate standoff technique rubber or
plastic layer serves to protect the flyer plate from the
explosive which, when detonated at one end of the flyer plate,
consist to strike the stationary plate with an impact
pressure much greater than the yield strengths of the metals
to be joined. If the velocity of the collision point is
less than the velocity of sound in two metals, a metal jet
is formed at the lower surface of the flyer plate, which
scours the interfacial surfaces. The explosive pressure then
bonds them together.

Denotation velocity of most explosive (7-8000 m/sec)
is significantly higher than the velocity of sound in the
materials to be joined (6000 m/sec.), the parall standoff
arrangement makes it difficult to satisfy the requirement

Explosive

$$VC = VD$$

VD ⟶

VC ⟶
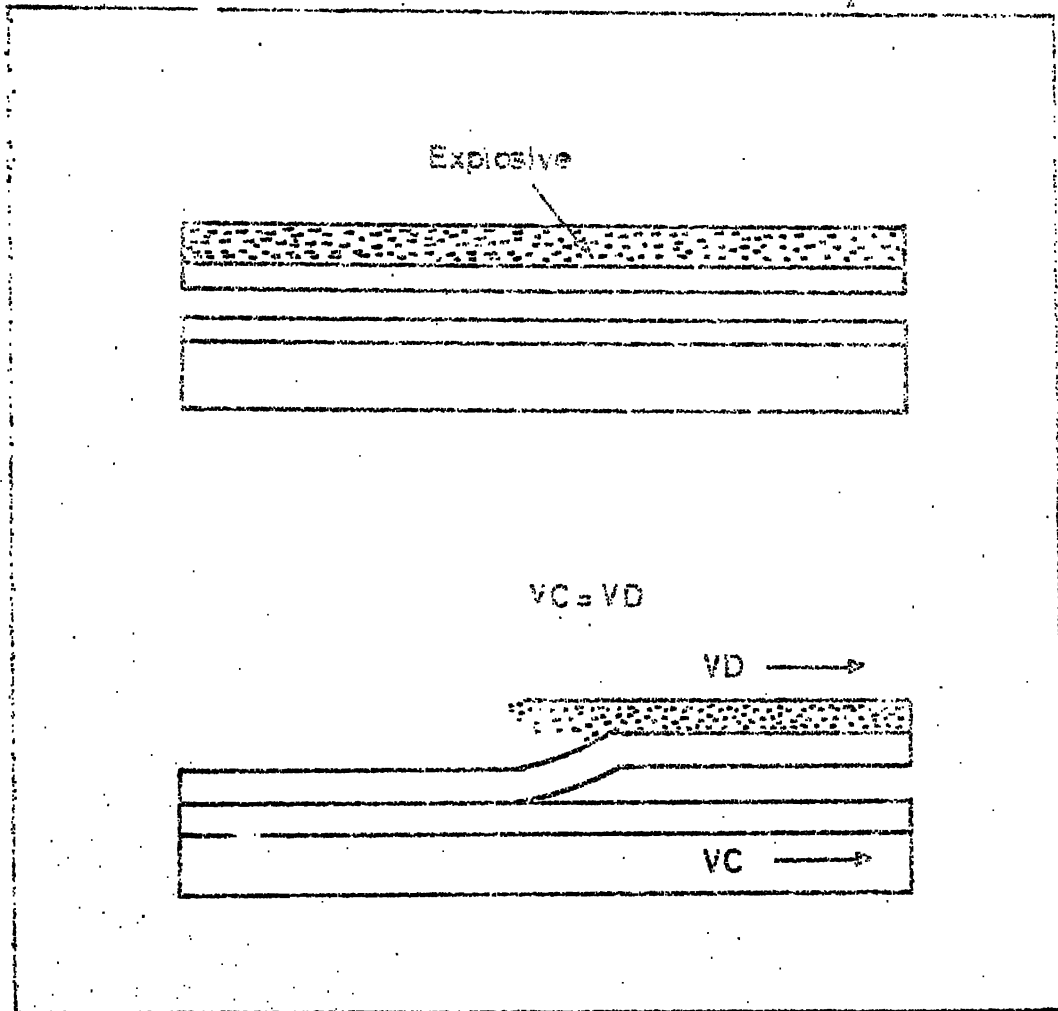
Fig:1·6   Schematic of explosive welding set-up parallel standoff . VD = detoration velocity , VC= velocity of the collison point .

(a)

(b)

a — Initial angle of inclination.
β — Dynamic bend.
γ — Collision angle.
Vc — Collision point velosity.

(C)

Fig. 1·7   (a)—Parallel plate arrangement.
(b)— Inclined plate arrangement.
(c)—Double flyer plate arrangement.

that the collision point be subsonic. Hence angular standoff is adopted to satisfy the bond requirements.

The range of material which have been explosively bonded is now extensive. Table 1.4.   shows the various combinations of metals that have been successfully bonded by this method. Plate area area as large as 300 ft^2 have been bonded commercially; flyer plate thickness upto 2" have been used. A lower limit is probably 0.001".

1.4.4 Spray forming

Spray forming is a relatively newer method for making thin metal strips.[21] It consists of atomising a liquid metal or alloy into the form of very small liquid droplets in a specially constructed chamber with a inert gas such as nitrogen. The droplets, which are 100 μm to 150 μm in diameter when in flight, were directed onto a cool surface where they were chilled and frozen rapidly in the shape of pancakes. Each chilled layer then formed the effective substrate for the next layer. A strong and coherent layer of metal was soon deposited which was peeled continuously from the substrate while it was still at a high temperature. The "as deposited" strip was relatively porous and was subsequently hot rolled to give a fully dense strip having similarities with 'hot band'. Peeling and hot rolling was done under an inert atmosphere to avoid oxidation caused

Liquid metal

Close — type atomiser

Spray chamber

Belt substrate

Gas fired furnace

Nitrogen

Deposited strip

Rolling mill stand(s)

Parting blade

Coil

To exhaust system
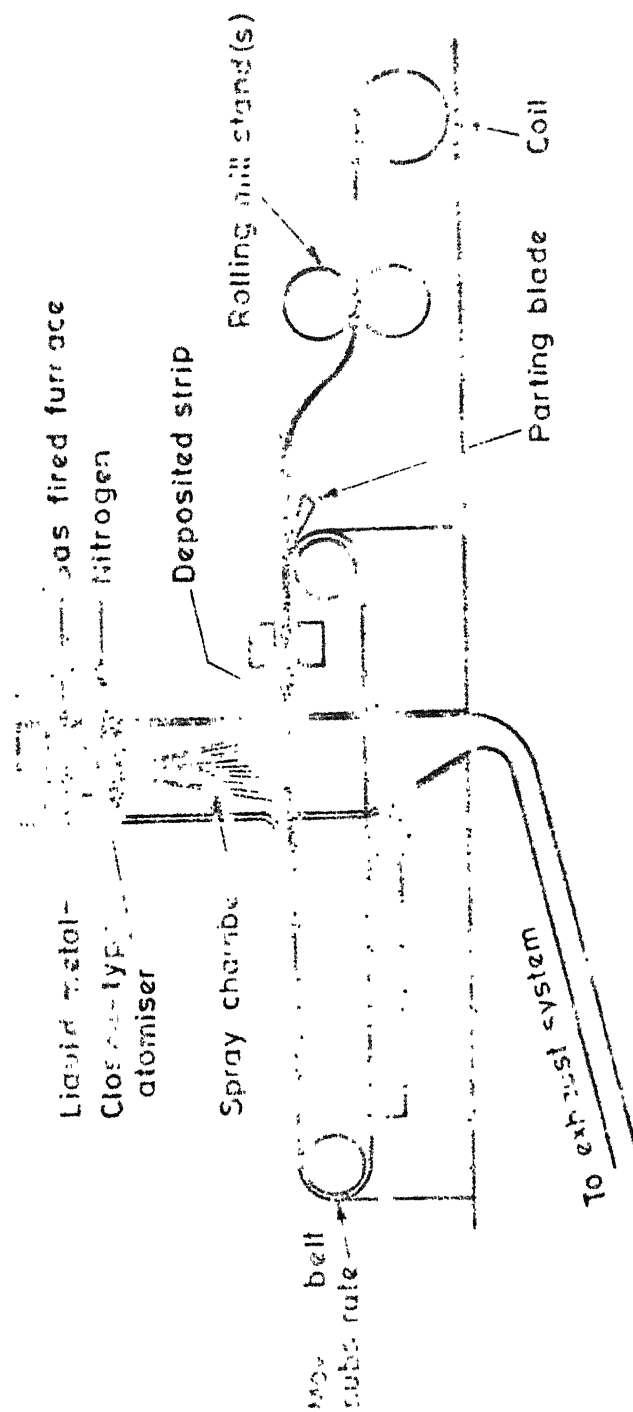
Fig.4.6 Schematic diagram of spray forming of thin strip.

Table 1.4

METAL COMBINATION BONDED BY EXPLOSIVE CLADDING

Metal	Zn	Ni + alloy	Nicrome	Pt	Zr	Ti	Bronze	Cupro-nickel	Brass	Cu	SS	Alloy Steel	Med C Steel	Low C Steel	Lead
	x	x						x	x	x	x			x	x
Low C steel					x	x	x	x	x	x	x		x	x	
Med C steel											x	x	x		
Alloy steel								x	x	x	x	x			
S.S.						x				x	x				
Cu		x								x	x				
Brass								x	x						
Cupro-nickel							x	x							
Bronze						x	x								
Ti					x	x									
Zr				x	x										
Pt			x	x											
Nicrome		x	x												
Ni and alloy	x	x													
Zn	x														

A blank space means bonding of that combination has not been attempted. It does not mean those metals can not be explosion bonded.

by the porosity. Subsequently the strip was cold rolled and annealed to produce the final strip. Fig. 1.'8 . shows Mark 1 equipment developed for strip making by this method.

In principle, the above method can also be used for making clad strip after little modification. After spray deposition of one metal to the required thickness, the other metal can be sprayed onto it. Soon after a composite clad strip is obtained which would be porous and relatively weak. Subsequently the porous clad strip could be hot rolled to full density, followed by suitable cold rolling and annealing treatment. Alternatively, the clad is sprayed on a suitabl prepared solid substrate (say in the form of plate) of the metal to be claded. The spraying will be done in inert atmosphere to avoid oxidation. The composite can be hot rolled to produce fully dense clad strip.[17]

Although the spray forming method has great potential for making clad strips, no published literature is available on it. However, considerable R&D work in this area had been conducted in the U.K., and the method is currently being used for making clad strips to be used for making bimetallic bearings.

1.4.5 Powder Metallurgy

Powder Metallurgy methods are important amongst the alternative methods developed to make this metal strips. Dube [22] has reported an extensive review of various PM

methods for making thin strips. Some of these processes have the capability of producing clad strips.

The original PM method for making metal strips consists of feeding metal powder into a specially constructed powder rolling mill, where the powder is subjected to sufficient pressure to form a self supporting green strip. The resulting strip is porous and weak and is subsequently sintered at high temperatures followed by densification either by hot rolling in one pass or repeated cold rolling and annealing. The finished strip produced has mechanical properties similar to those of conventionally produced material. The above process can be, in principle, be applied for making clad strips, after a little modification. Katrus and Vinogradov[23] have successfully produced three layer copper-iron-copper strips by powder rolling technique. The process consisted of dividing the hopper in three distinct zones, as shown in Fig. 1.-9 , through which three layers of powder was fed into the powder rolling mill. The resulting trimetallic strip was sintered at 940°C for 20 min, followed by single pass densification rolling at room temperature to 30-35% thickness reduction. The strip was further annealed at 850°C for 30 min. followed by 2-3 rolling passes to reach a thickness of 0.4 mm. The following table shows the typical mechanical properties of the trimetallic strip (22% Cu) after final annealing at 750°C for 1 hour :
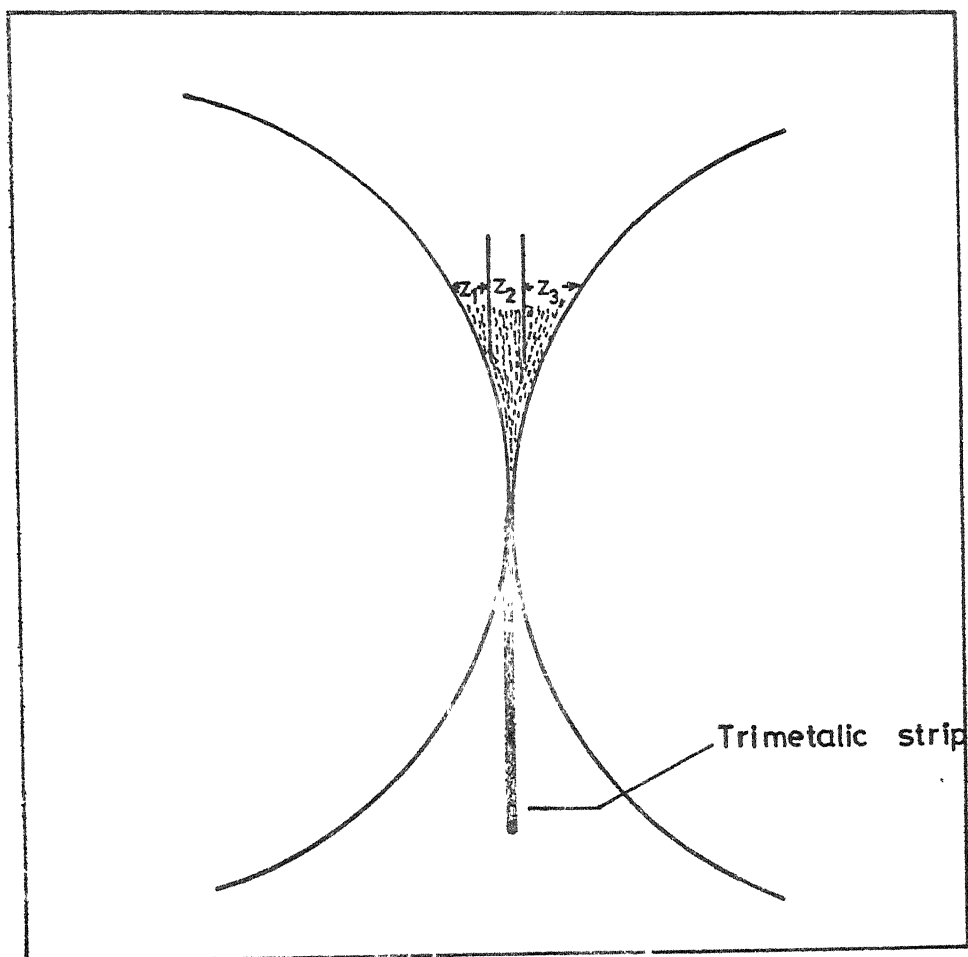
Fig. 1-9   Schamatic diagram of trimetalic
powder rolling mill .

U.T.S. = 29.7 kg/mm^2

% elongation = 20%

Another approach to make clad strip by PM is sintering the loosely placed powder on the surface of a backing strip, followed by densification rolling. Several research workers have attempted this method to make clad strips. Katrus et al has produced a bimetallic frictional elements by sinter-bonding powder of composition

Cu 68-76%, Pb 7-9%, Sn 8-10%, Fe 3-5%, Graphite 6-8% to a 0.08% C rimmed steel strip. at 800°C. The total thickness of the steel strip was 5 mm. The density of the sintered powder on the backing strip was about 3 g/c.c. The sintered strip was cold rolled to about 60% thickness reduction using rolls with diameter of 500 mm. The strip was then annealed at 700°C. It was given second cold rolling densification followed by annealing. Although the detailed mechanical properties are not reported, it has been reported that the clad strip possessed excellent wear resistance, enabling the brakes to operate for 6000 hour with the same set of linings.

The major difficulty encountered in the above process, although not reported in literature seems to be in a uniformly spreading of clading powder onto the backing strip surface, especially when the thickness of the clad layer is small. This problem can be overcome by depositing

a thin layer of metal powder suspension or slurry process. At the Institute of Material Science, Academy of Sciences of the Ukrainian S.S.R [24] a method has been developed in which a layer was deposited from a powder suspension nickel prepared from nickel powder and ethyl alcohol onto a specially prepared molybdenum strip. The suspension was dried and the composite was sinter-bonded. The subsequent processing is similar to that described earlier. The green porous layer obtained by deposition from a suspension does not adhere strongly to the metal substrate, and porous layer gets damaged during handling. The initial adhesion of the green porous layer can be increased by depositing a slurry prepared from metal powder and a binder solution. The bonding substance vaporizes almost completely during sintering leaving behind no residual impurity. The subsequent processing to produce the finished strip is similar to that described earlier. Katrus and Gribkov [25] have used this technique for preparing 0.2 mm thick nickel clad molybdenum strip having layer thickness ratio of 1:1. The clading of molybdenum strip with nickel greatly improved the mechanical properties of the former. For example, the number of bends on 2.5 mm radius mandrels was 49 for the Mo-Ni clad strip as against 25 for pure Mo strip.

1.4.6 A new proposed PM method for making metal strip

A new PM method has been proposed for making clad strips. The metal on which clading has to be done is referred to base metal in the present context. In principle, the method consists of preparing a homogeneous and free flowing slurry mixture from the powder of the base metal and a binder, which is cast into a strip form. The strip is dried and the slurry of the clad metal powder is deposited on the surface of the cast base metal strip. The deposited clad metal layer is dried.

The 'green' clad strip is then sintered at suitable temperatures to bring about the sintering within and between the individual layers. The sintered clad strip is hot rolled to form fully dense clad strip. The clad strip is cold rolled and annealed to produce finished strip.

CHAPTER - 2

OBJECT OF THE PRESENT INVESTIGATION

The objects of the present investigation were as follows .

1. To study the feasibility of making Nickel clad iron strip by the proposed powder metallurgy method.

2. To optimise the various process variables, such as relative thickness of the clad layer, hot rolling deformation, cold rolling deformation, etc. for the preparation of clad strip.

3. To evaluate the properties of the clad strip produced under optimum conditions.

CHAPTER - 3

RAW MATERIALS AND EXPERIMENTAL PROCEDURE

3.1 Raw materials

3.1.1 Iron powder

Iron-powder MH 300.25 manufactured by Hoganas Ltd., Sweden was used as base metal. The chemical composition and sieve analysis are shown in Table 3.1   .

3.1.2 Nickel powder

Carbonyl Nickel powder type 123 manufactured by INCO was used as clading metal for the present investigation. The chemical composition and powder characteristics are shown in Table 3.2 (a&b).

3.1.3 Binder

A binder was necessary to form a homogeneous slurry of the powder with sufficient viscosity. Reagent grade methyl cellulose powder was used as binder.

3.1.4 Gases

Pure hydrogen (IOLAR - grade) and Standard Nitrogen supplied in cylinders by the Indian Oxygen Ltd. were used.

3.2 Preparation of nickel clad iron strip

The preparation of nickel clad iron strip by powder metallurgy method consists of the following unit operations.

Table - 3.1

Characteristics of MH 300.25 Iron Powder

Upper particle size Taylor Mesh	300 (0.05 mm)
Apparent density	2.55 g/cc
Hydrogen loss	0.2% (0.3% max)
Carbon content	0.01%

Table - 3.1

Table - 3.2

Type 123 Nickel Powder
Typical Chemical Analysis - weight Percent

Element	% (wt.)	Element	% (wt.)
C	0.1 max.	Fe	0.01 max
O	0.15 max.	other element	trace
S	0.001 max.	Ni	balance

Table : 3.2 (b)
Typical Physical Characteristics

Characteristics

1. Average particle size
   (Fisher subsieve size) - Microns.   3-7

2. Apparent density g/cc   1.8-2.7

3. Specific surface area-m^2/g   0.34-0.44

1. Preparation of 'green' bimetallic strip

2. Sintering of 'green' bimetallic strip

3. Densification of the sintered strip by hot rolling

4. Cold rolling of the hot rolled bimetallic strip

3.2.1 Preparation of the 'green' nickel clad strip

Two different methods for making green strip viz. die compaction method and slurry method were used for making green strip.

3.2.1.1 Die compaction method

67 gms. iron powder mixed with 1% zinc stearate was compacted into a strip of size 7 cmsx5 cmsx0.5 cm using a load of 15 ton. The top plunger was removed from the die and then 12 gms of nickel powder mixed with 1% zinc stearate was spread over the compacted iron strip surface. Every care was taken to spread the powder as uniform as possible. Subsequently the composite powder mass was compacted using a load of 40 tons. The composite strip was subsequently withdrawn from the die.

The greatest difficulty encountered in preparing green strip by the technique was the uniform distribution of nickel powder on the surface of compacted iron powder especially around the iron : nickel ratio of 5:2. Therefore, it was not used for the detailed experimental investigation.

3.2.1.2 Slurry method

A slurry of iron powder was prepared using the following ratio of the different ingredients .

Iron powder	70.9 %
Methyl cellulose	: 0.7 %
Water	: 28.4 %

A power driven stirrer was used for making slurry. The slurry was free flowing and homogeneous. It was poured into a mould of size 10 cmx8 cmsx0.5 cm and then mould. was kept on a hot plate for drying. A thin coating of oleic acid was applied on the mould surface in order to facilitate the release of dried strip. After drying the strip got released from the mould surface,subsequently the depth of the mould was increased to the required size and then nickel slurry was poured on the dried iron strip surface.

The nickel slurry was prepared using the following ratio of the different ingredients :

Nickel powder	: 71.0%
Methyl cellulose	: 0.6%
Water	: 28.4%

For the present investigation Fe-Ni clad strips of the ratio 5:0.5, 5:1, 5:2, 5:3, 6:2, 8:2 and 10:2 by ~~weight~~ thickness were prepared.

3.2.2 Sintering of the green bimetallic strip

The green Fe-Ni clad strip obtained by the slurry method had density about 2.60 -2.28 gm/cm^3, which corresponded to 65-70% porosity level.

The green clad strip was sintered at 1000°C for 30 minutes in hydrogen atmosphere. The sintering chamber consisted of an long inconel muffle, 750 mm long and 100 mm internal diameter, which was externally heated by silicon carbide rods. The open end of the furnace had a 200 mm long cooling chamber externally cooled with flowing water, where the sintered strips were cooled to about 70°C under hydrogen atmosphere prior to their taking out from the furnace. The gases were introduced in the chamber through a 6 mm internal diameter stainless steel tube passing through the open end of the chamber and were released near the closed end. The hydrogen gas coming out of the furnace was burnt near the exit.

The standard procedure for the sintering was that the sintering chamber already maintained at the required temperature, was flushed with nitrogen for about 5 min. before introducing hydrogen into it. The green clad strip, placed on a perforated inconel tray, was then pushed carefully into the hot zone of the furnace. After sintering the strips for the required period of time, they were cooled in the cooling zone.

3.2.3 Hot-rolling densification of the sintered clad strip

The bimetallic strip produced by sintering contained 50-55% porosity. High temperature and longer sintering time gives more densification, but fully densified strip cannot be produced by sintering itself. The densification was carried out by hot rolling the sintered clad strip.

The preheating prior to hot rolling was carried out at 1150°C for 30 min. in hydrogen atmosphere. Preheating in hydrogen was necessary in order to avoid any oxidation of the strip caused due to the interconnected pores. It also helped in reducing any oxide film formed on the powder surface. One end of the reheating furnace was closed while the other end had a zone projecting outside the furnace as shown in fig. 3.1. The reheating chamber contained a flat plate of Inconel as a base for the strip. The hot rolling was performed on a 2-high mill having 135 mm diameter rolls rotating at a speed of 72 rpm and maintained at room temperature. As far as possible the thickness reduction by hot rolling was given in a single pass. In situation where it was not possible for the rolls to grip the strip, the required thickness reduction by hot rolling was given in 2 or 3 passes.

The standard procedure for hot rolling was as follows :

1. A small hole was drilled near one edge of the sintered strip.
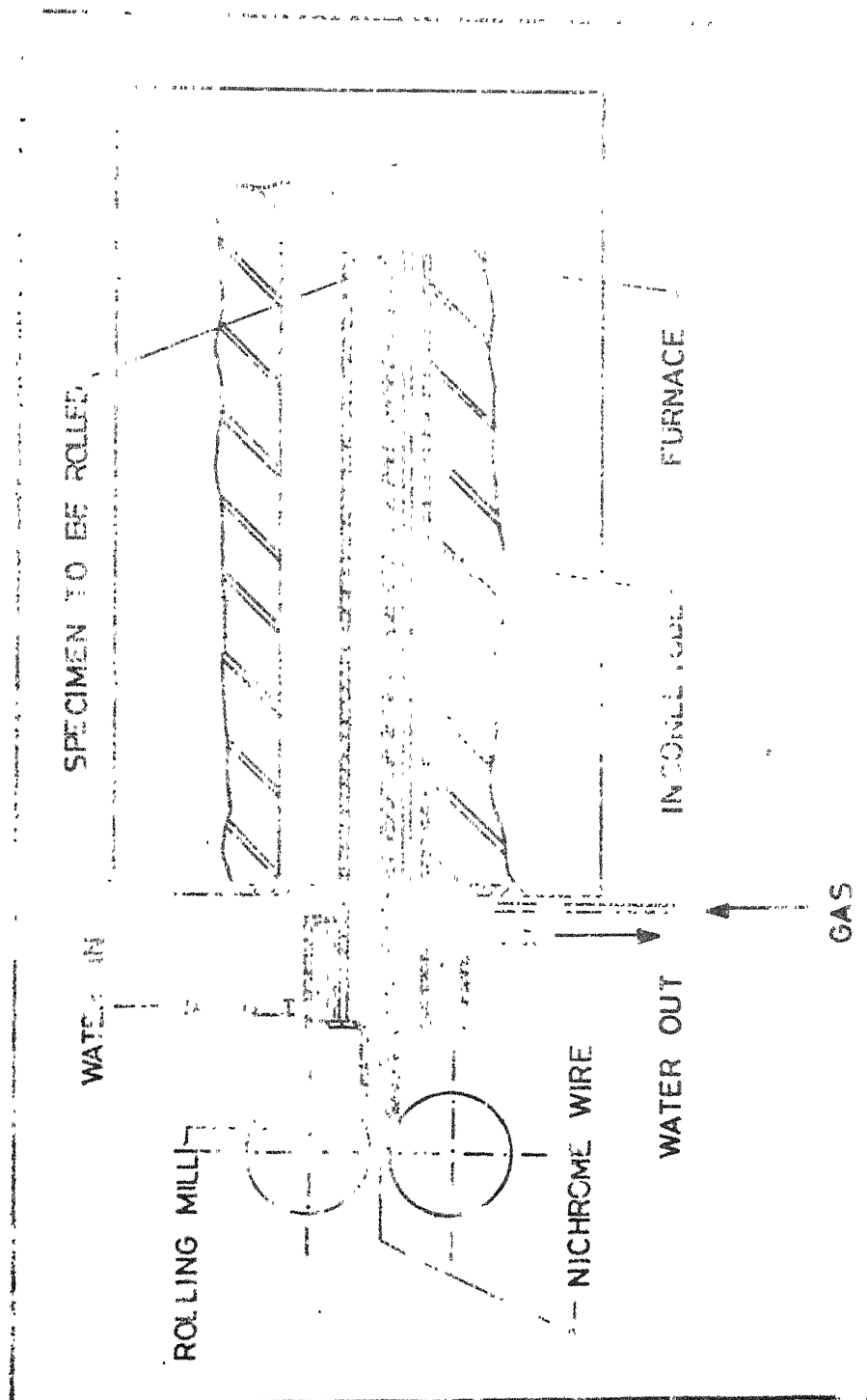2. A long nicrome wire of 28 gauge was tied to the strip.

Fig. 3.1 Hot rolling arrangement.

3. The sintered strip was introduced into the hot zone of the reheating furnace.

4. Reheating furnace was placed in front of the rolling mill so that the extended exit and of the furnace was very close to the rolls.

5. The roll gap was adjusted to the required and after preheating strip for required period of time it was pulled in between the rotating rolls with the help of the attached nicrome wire.

6. The hot rolled strip coming out from the mill was cooled in a bed of graphite chips for 5-10 min. in order to prevent oxidation.

The above procedure produced satisfactory hot rolled clad strip without any internal oxidation. The hot rolled strip were then annealed at 700°C for 30 min. in hydrogen atmosphere. This removed cold working on the surface of the clad strip caused by the cold rolls.

3.2.4 Cold rolling and annealing of the hot rolled annealed clad strip

Hot rolled and annealed clad strip was cold rolled to further decrease the thickness of the clad strip and to improve the mechanical properties and surface finish. The cold rolling was done on the same rolling mill using cold rolls and machine oil as a lubricant. The direction of the cold rolling was parallel to that of the hot rolling in all the cases.

The percentage thickness reduction given by cold rolling was 20, 30, 40, 60, 70 and 80%. Subsequently the clad strips were annealed at 700°C for 90 min. Separately in hydrogen or nitrogen atmosphere. It was observed that during the cold rolling the strips behaved like a monometal and very thin strip (upto 0.15 mm) thickness can be produced. It was also observed that there was no problem of edge cracking or delamination.

3.3 Evaluation of properties

3.3.1 Density

The density of the clad strips was measured by weight and dimension method. The density of fully dense clad strip was measured by 'Archimedes Principle'.

3.3.2 Mechanical properties

The 0.2% proof stress, U.T.S. and percentage elongation of the strips were determined using an Instron Universal Testing Machine at a cross-head speed of 0.5 mm/min. and chart speed of 20 mm/min. All the testing was done at room temperature and parallel to the cold rolling direction.

Because of the shortage of the strip, the size of the specimen used for mechanical testing, as shown in fig. 3.3.2 was not according to the BS 18 specification for thin strips and sheets. However, the geometry of the specimen was maintained according to the above specification.

Specimen thicker than 0.5 mm was prepared with a special die by filing. A great care was taken to prepare the specimen of porous strips.

For thinner strips a die-punch set up was used for punching out tension specimen. Any <u>burr</u> formed on the punched specimen was removed by polishing with fine grade emery paper.

A minimum of three specimens were tested and the means was calculated.

3.3.3 <u>Bond test</u>

A simple method of judging the bond strength is to see whether cracks are formed on bending the strip. The strip were bent to 180° and then the outer surface was observed for any crack formation.

3.3.4 <u>Structural properties</u>

The structure of the clad strip at various stages of the processing was examined under optical and scanning electron microscopes.

3.3.4.1 <u>Optical microscopy</u>

The porous nickel clad iron strip after sintering was soft and brittle, and cold not be prepared for metallographic examination by the usual method. It was necessary to impregnate the pores with epoxy resin which could be cured subsequently.

A mixture of Araldite epoxy resin CY 212 and hardner HY 951 in the proportion of 10:1 by weight was used for this purpose. Fully dense strips were also mounted in epoxy resin prior to their polishing. Standard polishing procedure was used.

For fully densifie d strips, the specimens were first etched in 2% Nital soln. for iron and 1:1 Acitic acid and conc. HNO_3 soln. for nickel.

3.3.4.2 Scanning electron microscopy

The fractured surface of the strips produced by hot rolling to different thickness reduction were examined with scanning electron microscope without coating the specimens.

RESULTS AND DISCUSSION

4.1 Effect of Temperature and Layer Thickness on the Sintering Behaviour of Fe-Ni Clad Strip.

Table 4.1 shows the effect of temperature on the sintering behaviour of Fe-Ni clad strip having thickness ratio of Fe and Ni as 5:2. It can be seen that nickel powder sintered well when heated at 900°C for 30 min., while the iron layer did not. However, when the sintering temperature was raised to 1000°C, both the nickel and iron powder sintered well, but delamination and curling of the strip was observed. The superior sinterability of nickel as compared to iron at 900°C is due to its finer powder size and lower sintering temperature. By trial and error, it was found that when the strip is introduced in the hot zone of the furnace kept at 950°C and then the temperature is raised to 1000°C (it took about 30 min. to reach a temp. of 1000°C), the delamination in the strip did not occur. It clearly shows that the rate of heating is important in controlling the delamination, especially when the powders of varying sintering characteristics are used.

Table 4.1 : Observation on the effect of sintering temperature
on the behaviour of Fe-Ni clad strip during
sintering (Fe : Ni : 5:2)

S.No.	Sintering temp.°C	Sintering time, min.	Observation
1	900	30	Nickel powder sintered very well, whereas the iron powder particles did not sinter
2	950	30	Nickel powder sintered very well. There was some sintering in the iron powder mass.
3	1000	30	Nickel powder sintered very well. There was also considerable sintering in the iron powder mass. Delamination of the clad strip was observed. There was some curling in the strip
4	1050	30	---do---
5	The strip introduced in the hot zone kept at 950°C and then the temperature was raised to 1000°C, which took about 30 min. to reach	30	Sintering in both nickel and iron powder mass was perfect and no delamination of the layer was observed. There was also no curling in the strip.

Table 4.2 · Observation on the effect of relative thicknesses of Fe-Ni layer on the sintering behaviour of the Fe-**Ni** clad strip.

Base metal (Fe) thickness in mm	Cladding layer(Ni) thickness in mm.	Thickness ratio Fe:Ni *	Fe:Ni weight ratio	Observation
5	0.5	10	10.22	Cladding layer cracked during sintering
5	1	5	5.11	Almost crack free surfaces
5	2	2.5	2.55	No surface crack
5	3	1.66	1.70	- do -
6	2	3	3.06	- do -
8	2	4	4.08	- do -
10	2	5	5.11	- do -
10	1	10	10.22	- do -

*Iron and nickel layers had a 65 and 70% porosity, respectively.

Table 4.2 shows the effect of relative thickness of Fe
and Ni layer on the sintering behavior of the Fe-Ni clad
strip. It can be seen that it is not only Fe-Ni thickness
ratio is important but also the thickness of nickel layer.
For example, the clad strip having Fe/Ni thickness ratio of
10 and iron and nickel layer thickness of 5 mm and 0.5 mm
respectively exhibited surface cracks on the nickel layer
during sintering, while the strip having same Fe/Ni thickness
but iron and nickel layer thickness of 10 and 1 mm respectively
did not exhibit any surface crack.

Fe-Ni clad strip of having iron and nickel layer
thickness of 5 mm and 2 mm was used in subsequent studies.

4.2 Hot rolling of the sintered Fe-Ni clad strip

The porous Fe-Ni clad strip behaved well during hot rolling
at deformation of 50% and above. Only a small edge cracking was
observed. Below 50 percent thickness reduction the hot rolled
strip had some transverse surface cracks. This demonstrates that
the porous sintered clad strip had sufficient strength and
ductility to enable it to withstand the stresses involved during
hot rolling. Fig. 4.1 shows the variation of density of Fe-Ni
clad strip with percentage thickness reduction by hot rolling.
It can be seen that the density continuously increases with
percent thickness reduction, and a limit is reached after which
there is no effect of hot rolling on density. It is apparent
that 80 percent thickness reduction is needed to achieve
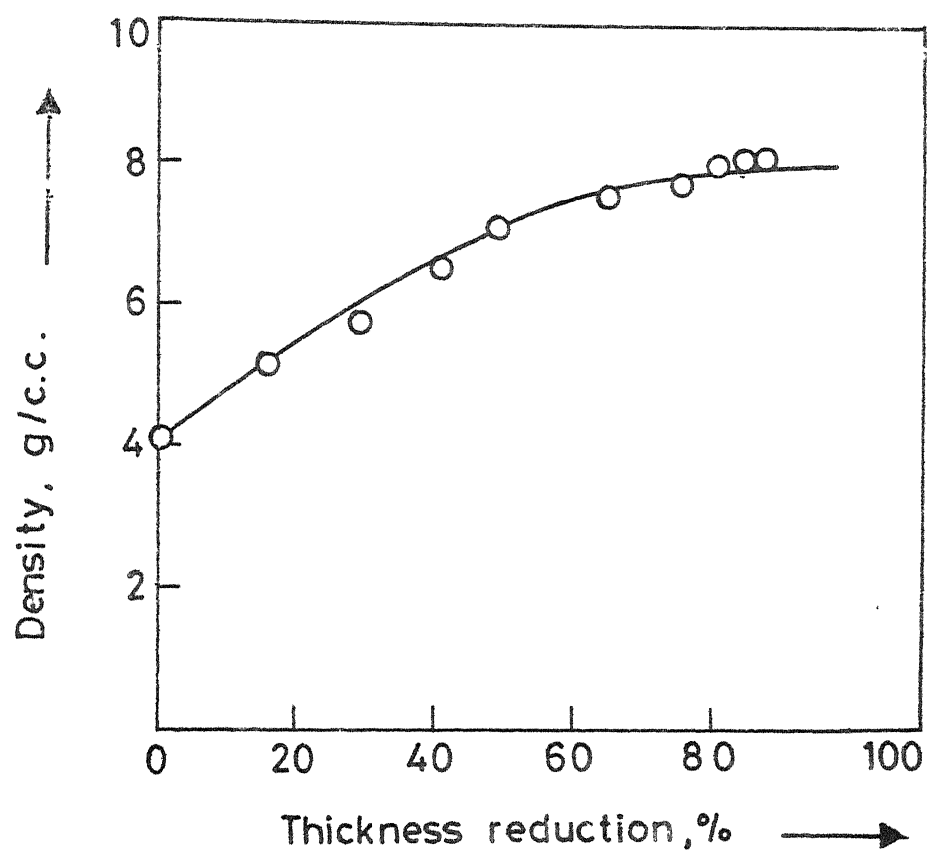full density in the clad strip.

Fig: 4·1 Effect of amount of thickness reduction by hot rolling on the density of the strip.

4.3 Pore-Morphology during hot rolling of the Fe-Ni clad strip

Pore-Morphology of Fe-Ni clad strip was monitered by optical and scanning electron microscopy.

Fig. 4.2 shows the SEM view of the interface of the hot rolled to various thickness reductions. It can be seen that the interface of the strip hot rolled to 16% thickness reduction had a gap which progressively diminished as the hot rolling deformation increased. At about 40% thickness reduction by hot rolling the gap at the interface vanished as the layers of Fe and Ni were in intrimate contact with each other.

Fig. 4.3 shows the SEM view of the iron area of the Fe-Ni clad strip hot rolled to various thickness reductions. It can be seen that the fine porosity present in the sponge iron powder gradually decreased with hot rolling deformation, and it is apparent that the iron powder in the clad strip hot rolled to about 49% thickness reduction did not have any intra-particle porosity. It is also apparent that the shape of the iron powder did not change up to 29% thickness reduction. However, beyond about 40% thickness reduction the iron powder particle starts elongating in the direction of hot rolling. It can be observed that the physical movement of the iron powder in the strip was mainly in the thickness direction up to 40% thickness reduction. Beyond 40% thickness reduction, the plastic deformation of the iron powder starts.

Fig. 4.4 shows theSEM view of the nickel area of the Fe-Ni clad strip hot rolled to various thickness reduction. It can be seen that the shape of the nickel particle did not change up to 29% thickness reduction. The nickel particle starts elongating beyond 40% thickness reduction. It is apparent that longitudinal flow in the nickel powders is less than that in iron powders at the same hot rolling level. (Fig. 4.3(c) & Fig. 4.4(c), and Fig. 4.3(d) & Fig. 4.4(d)).

4.4 Efficiency of densification by hot rolling

The efficiency of densification of the porous clad strip by hot rolling, E was calculated according to the relation.

$$E = \frac{\rho - \rho_0}{\rho_s - \rho_0} \times 100$$

where ρ = density of the hot rolled strip

ρ_0 = density of the starting strip

ρ_s = density of fully dense strip

The density of fully dense Fe-Ni clad strip was taken to be 8.11 g/cm^3.

Fig. 4.5 shows the relation between the efficiency of densification and percent thickness reduction by hot rolling. The dotted curve in the figure represents the efficiency of densification which would be expected if all the deformation was used in closing the pores of the strip without any increase in
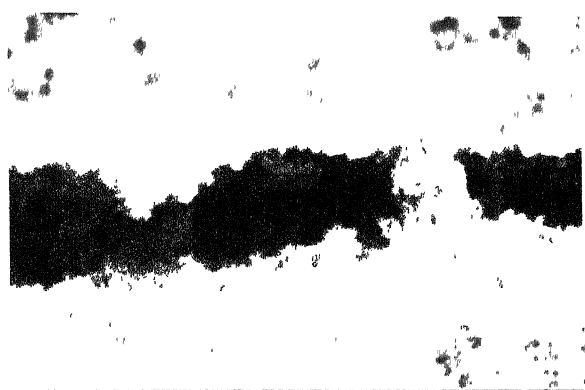
(a)
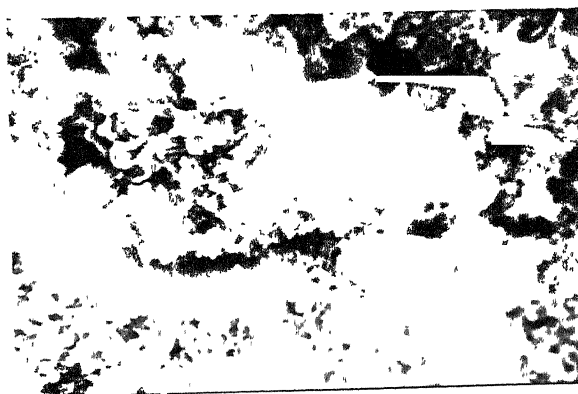
(b)

(c)

Fig. 4.2 . SEM view of the fractured interface of Fe-Ni
clad strip.

(a) 16% HR (X 192) (b) 29% HR (X 192)
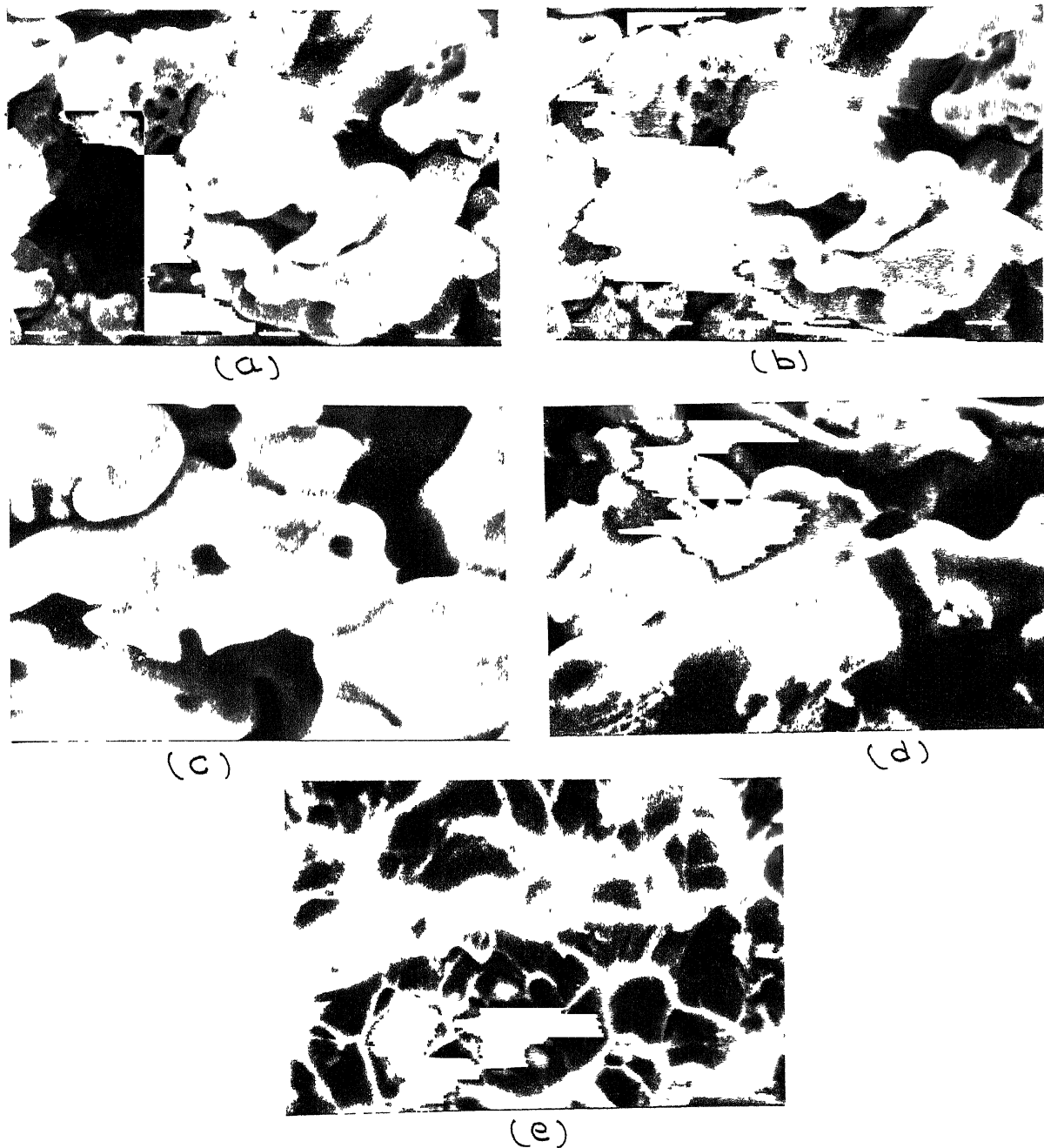
(c) 40% HR (λ 192)

Fig. 4.3 . SEM view of the fractured surface of Fe-Ni clad
strip (iron area)

(a) 16% HR (X 768) (b) 29% HR (X 768)

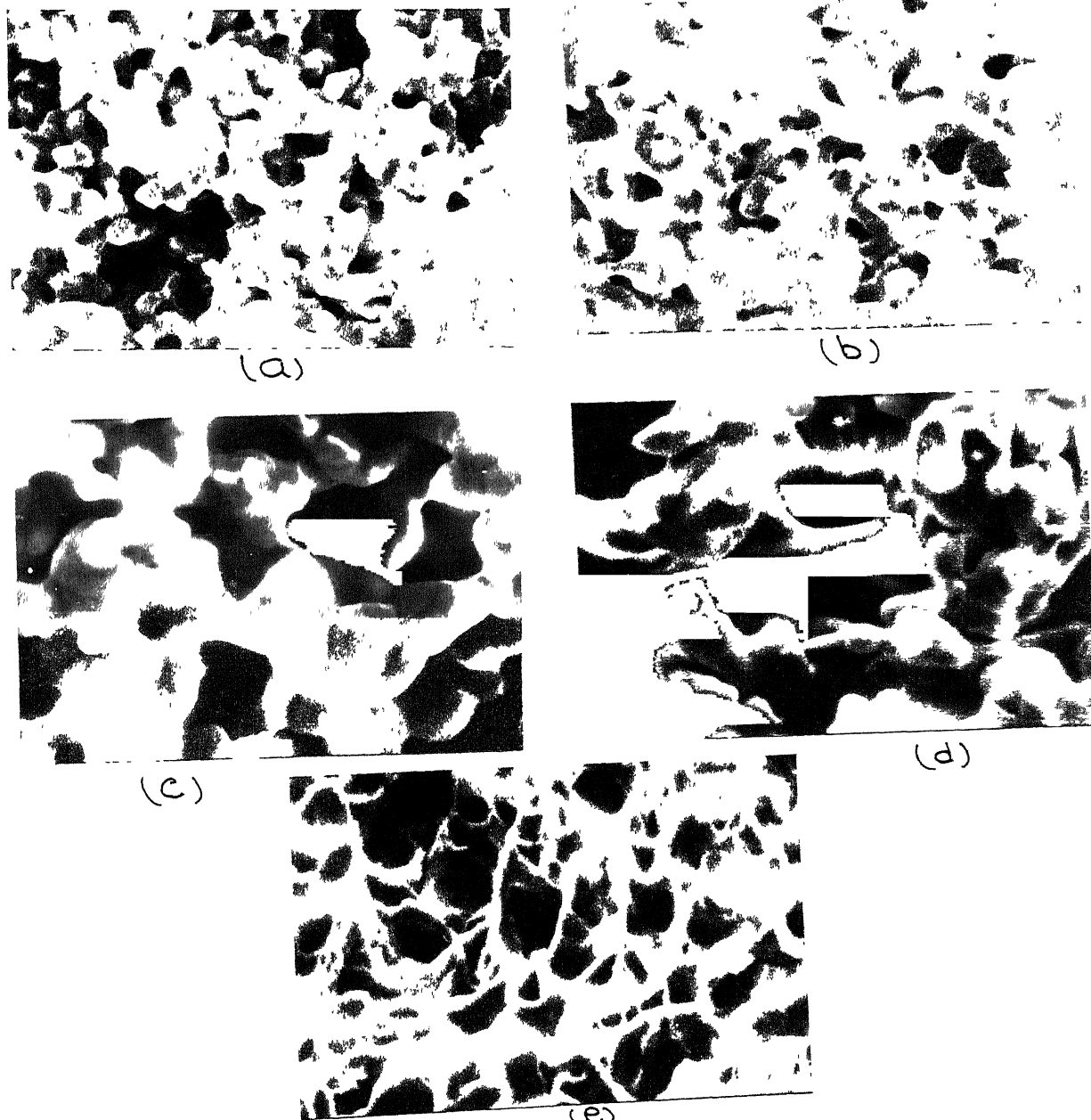(c) 40% HR (X 768) (d) 49% HR (X 768)

(e) 64% HR (X 768)

Fig. 4.4. SEM view of the fractured surface of Fe-Ni clad
strip (Nickel area).

(a) 16% HR (X768) , (b) 29% HR (X 768),

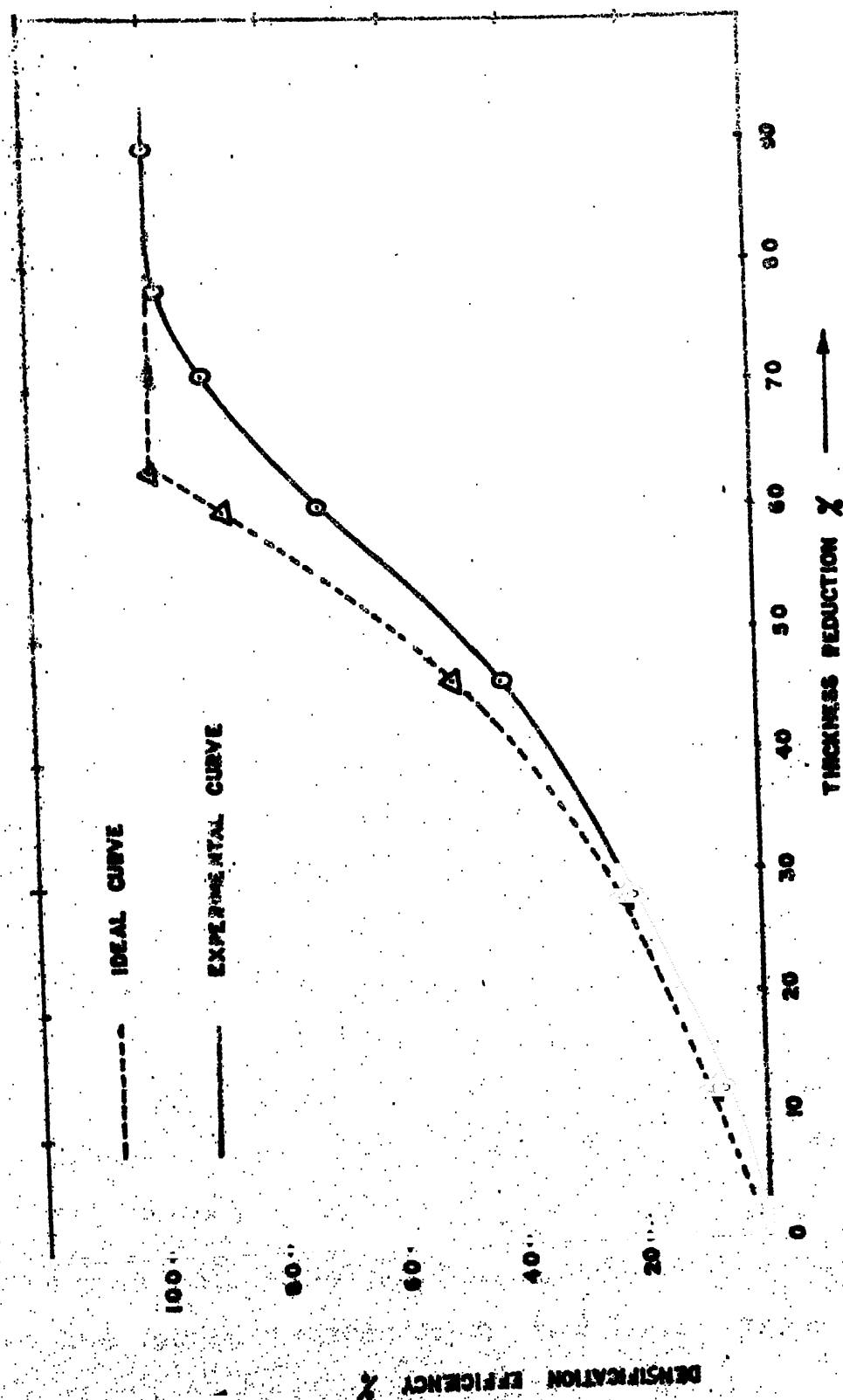(c) 40% HR (X 768) , (d) 49% HR (X 768),

(e) 64% HR (X 768).

FIG:-4, EFFICIENCY OF DENSIFICATION DURING HOT ROLLING OF Fe-Ni STRIP

length of the strip. The difference between the ideal and the actual efficiency was not significant up to 40 percent thickness reduction, but the actual densification becomes less efficient beyond this deformation. This is due to the fact that some of the deformation goes in to longitudinal direction, thereby increases the length of the strip.

4.5 Longitudinal flow during hot rolling

Porous sintered Fe-Ni clad strip behaves like a viscous solid and condition for its deformation which have to be satisfied are that of constant mass.

Therefore the total longitudinal flow produced in the Fe-Ni clad strip by hot rolling was lower than which would have been produced in fully dense material.

The ratio between flow in the length direction and the thickness direction during hot rolling can be expressed by an apparent plastic poisson's ratio

$$\nu = -\frac{1}{2} \frac{d\epsilon_\ell}{d\epsilon_t}$$

where ϵ_ℓ and ϵ_t are true strains in the length and thickness direction. For a fully dense material the value of plastic poisson's ratio is 0.5. However, for a porous material the poisson's ratio is less than 0.5 and is a function of its relative density.

Fig. 4.6 shows the relationship between true length strain and true thickness strain of the clad strip. The dotted
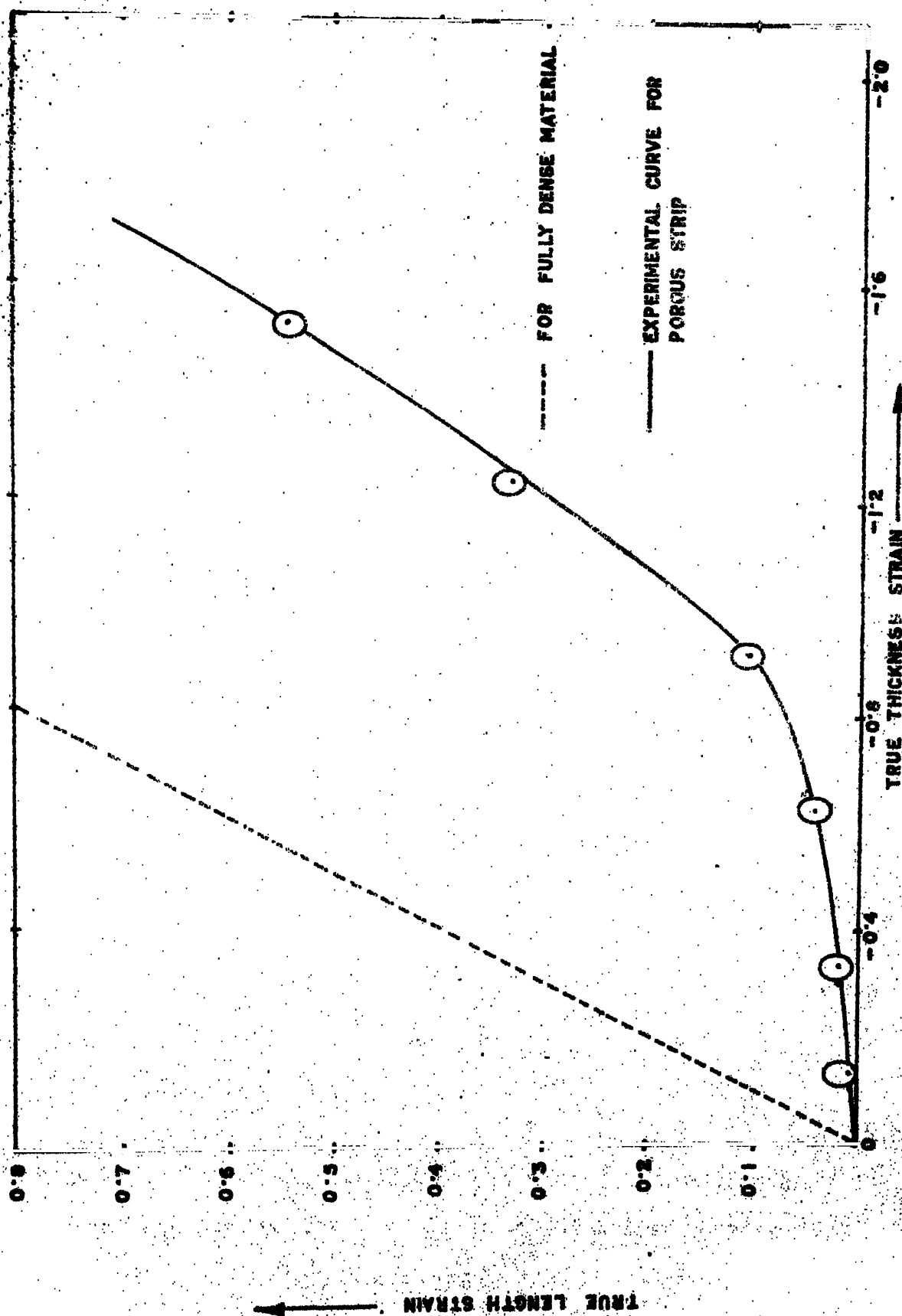
FIG:— RELATIONSHIP BETWEEN TRUE THICKNESS STRAIN AND TRUE LENGTH STRAIN BY HOT ROLLING OF Fe – Ni STRIP.

curve is for the fully dense material. It can be seen
that the true length strain is very small up to true thickness
strain of -0.61, which corresponds to 40% thickness reduction.
Therefore, the value of plastic poisson's ratio was very
small up to 40% thickness reduction. However, beyond this
value, the true length strain increased and so the plastic
poisson's ratio. Beyond true thickness strain of -1.23,
which corresponds to 71% thickness reduction, the true longi-
tudinal strain was equal to the thickness strain and the straight
line become almost parallel to the dotted line for fully
dense material.

4.6 Effect of hot-rolling deformation on the mechanical properties of Fe-Ni clad strip

All mechanical properties were measured after annealing
the hot rolled strip at 700°C for 30 minutes in hydrogen to
remove work-hardening on the surface of the strip due chilling
caused of the surface of the strip by cold rolls.

Fig. 4.7 and Fig. 4.8 shows the changes in the tensile
strength and percent elongation of the strip as a function
of hot rolling deformation. It can be seen that the percentage
elongation remained virtually constant at a very low value
up to 40 percent thickness reduction and increased rapidly
after this deformation level and became constant after 80%
thickness reduction. It can also be seen from fig. 4.8 that
the U.T.S. continuously increased with percent thickness
reduction with a slow rate up to 40% thickness reduction.
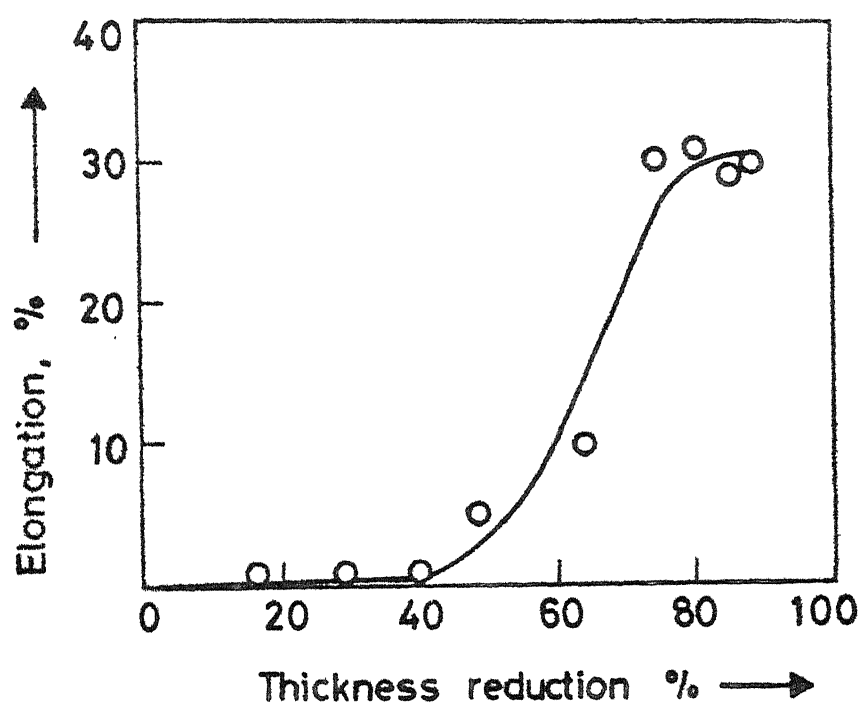
Fig: 4.7 Effect of amount of thickness
reduction by hot rolling on the elongat -
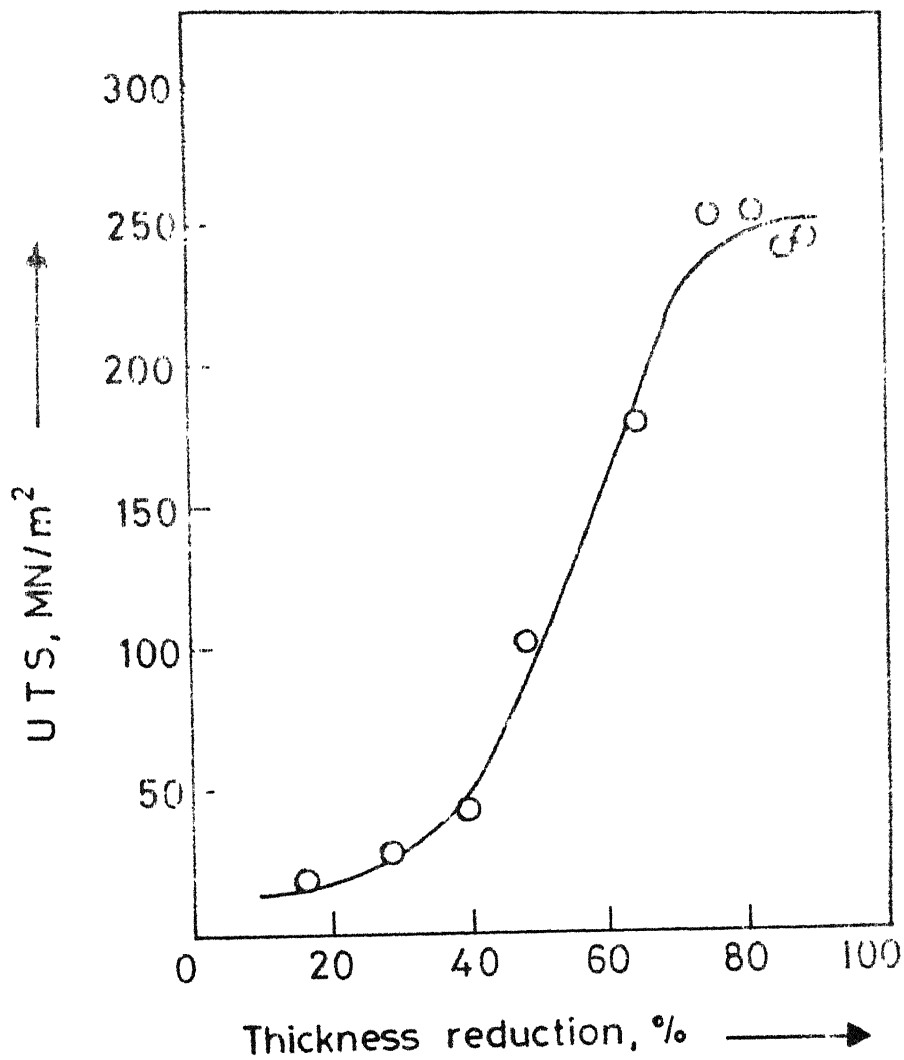ion of the strip.

Fig: 4.8 Effect of amount of thickness red - uction by hot rolling on the ultimate ten - sile strength of the strip .

After this value of thickness reduction the U.T.S. increases very rapidly. After 80% thickness reduction there is no effect of hot rolling thickness reduction on the U.T.S.

As seen earlier, before 40% thickness deformation the physical movement of the powder particle was predominantly in the thickness direction. The area of contact between powder did not change considerably. Beyond 40% thickness deformation the plastic deformation of the powder starts and the area of contact between powder particles increased substantially. This explain why the mechanical properties increased considerably beyond 40% thickness reduction.

4.7 Properties of the fully dense hot rolled and annealed Fe-Ni clad strip.

The mechanical properties of the fully dense hot rolled annealed Fe-Ni clad strip is shown in Table -4.3.

It can be seen that the strip has acceptable mechanical properties.

Fig. 4.9 shows the microstructure of the fully dense hot rolled strip in the unetched and etched conditions.

Table 4.3 : Mechanical properties of the Fe-Ni clad strip (Fe:Ni :: 5:2).

U.T.S., MN/m^2	264
0,2% proof stress, MN/m^2	86
Elongation %	32
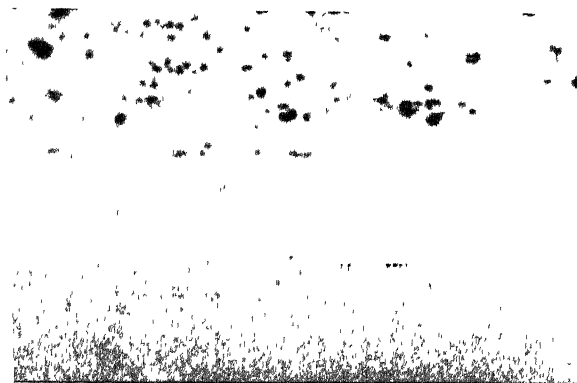
(a)
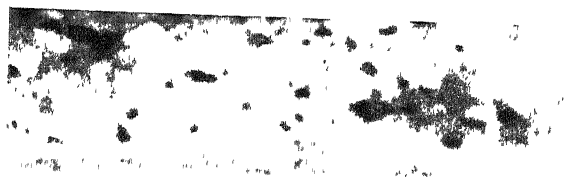
(b)

Fig. 4.9. Microstructures of interfaces of hot-rolled
annealed Fe-Ni clad strip.

(a) 81% HR unetched (X 200)

(b) 81% HR etched (X 200)

4.8 Cold-rolling behavior of fully densified hot-rolled annealed Fe-Ni clad strip.

Hot rolled and annealed Fe-Ni clad strip was further cold rolled to improve the mechanical properties and surface finish. The clad strip behaved well during cold rolling. 80 percent thickness reduction can be given without any intermediate annealing.

Fig. 4.10 and Table 4.4 shows the relationship between U.T.S. and percentage elongation of the annealed strip and thickness reduction by cold rolling prior to annealing. It can be seen from the above fig. that the percentage elongation of the finished annealed strip increased continuously up to 50% and after that it decreased. In case of UTS it remained almost constant up to 50 percent cold rolling prior to annealing and beyond this reduction it also decreased.

Fig. 4.11 shows the microstructure of cold rolled and annealed Fe-Ni cold strip. It can be observed that the nickel layer is free from inclusions. This is obvious because nickel powder used was carbonyl nickel which did not contain any non-metallic inclusions. Further the iron layer contains fine inclusions, which originated from the non-metallic oxides present in the starting sponge iron powder. It is clear from the fig. 4.10 and Table 4.4 that the optimum amount of cold rolling prior to annealing seems to be about 50% As stated above, the iron layer contained some fine non-metallic inclusions which are uniformly distributed throughout the matrix.
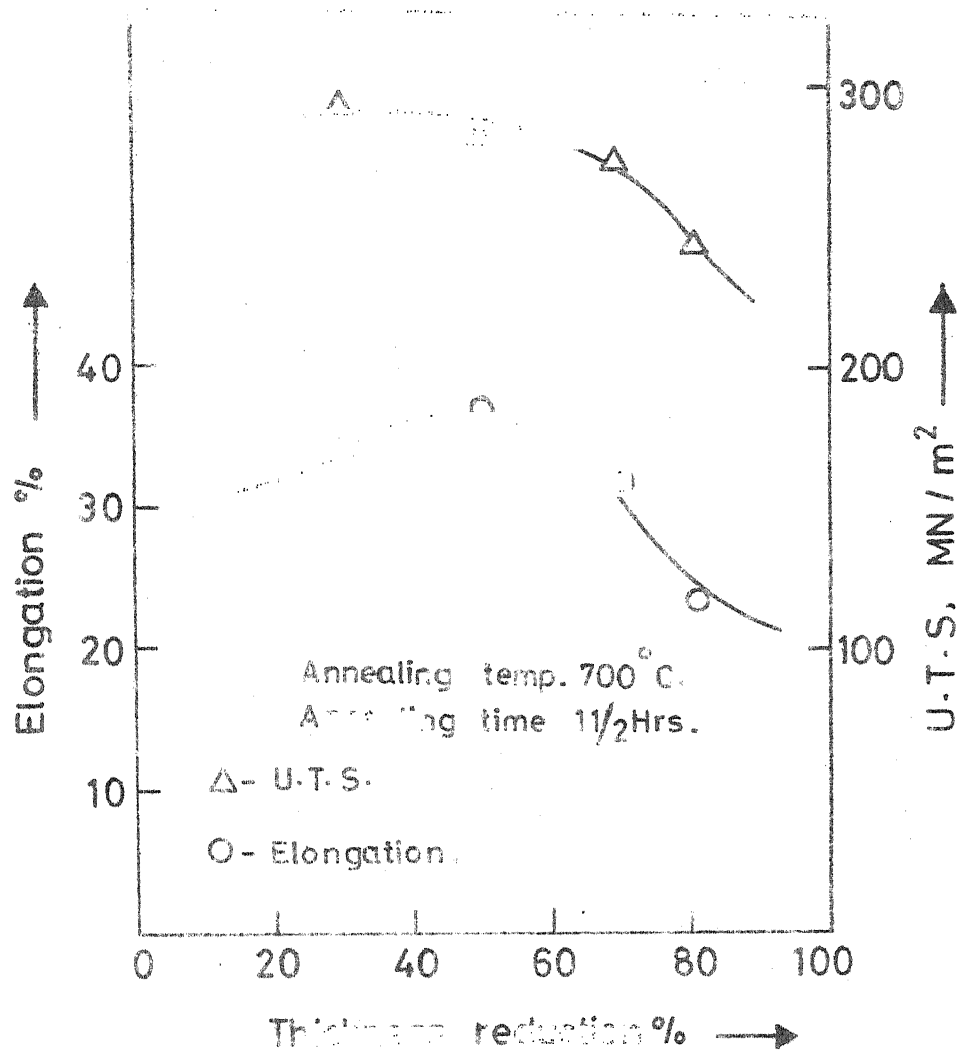
Fig: 4·10 Effect of amount of thickness reduction by cold rolling on the ultimate tensile strength and elongation of the annealed clad strip.
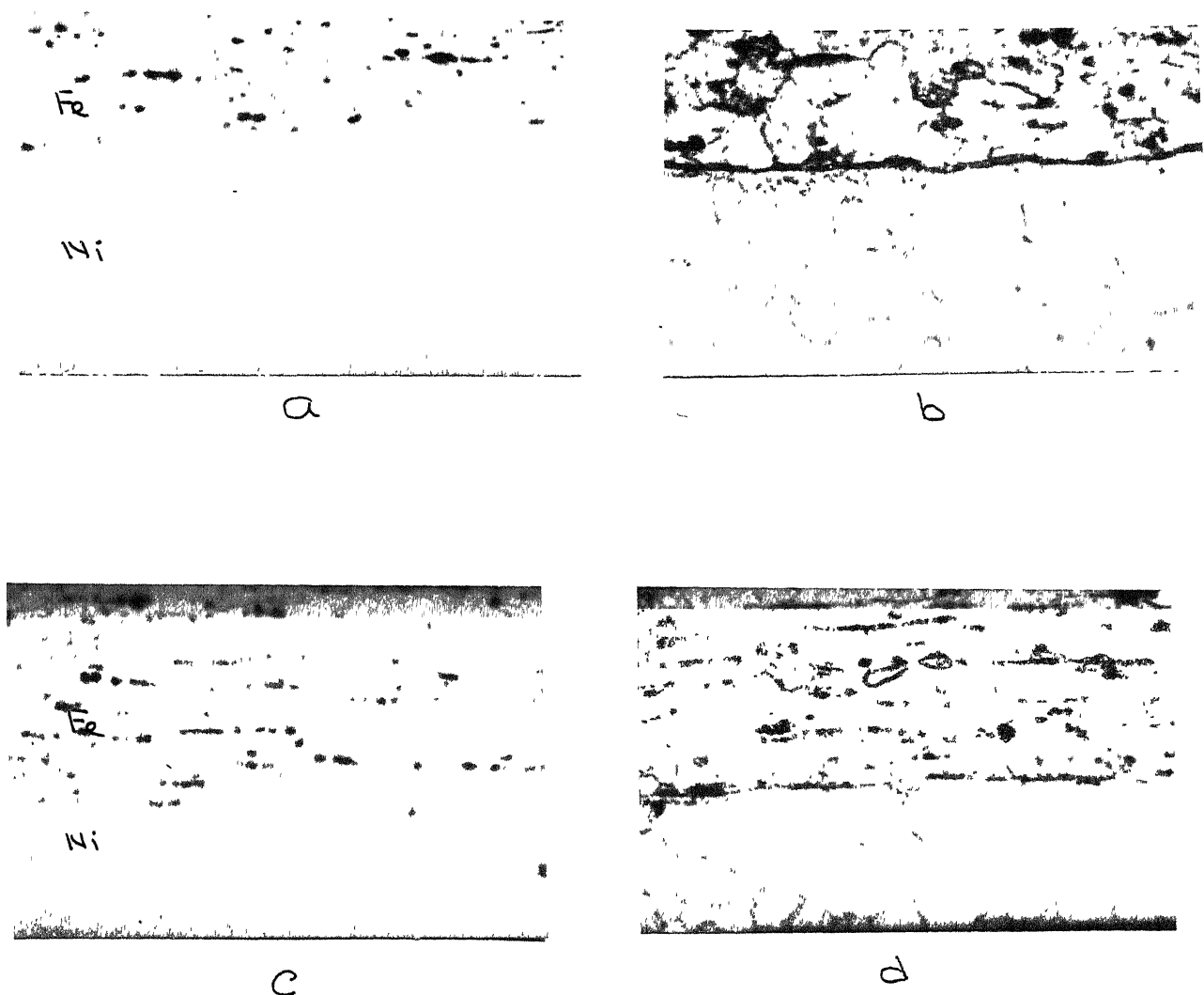
Fig. 4.11 Microstructures of interfaces of Fe-Ni clad strip
at different cold rolling thickness reduction
prior to annealing.

(a) 50% CR   etched (X 200)

(b) 50% CR etched (X 200) for Ni (Acitic acid: Nitric Acid 1:1)

(d) 70% CR etched (Acitic acid :Nitric acid.1:1),(X200)

(c) 70% CR etched (X 200).

It appears that the cold rolling of such strip beyond 50% thickness reduction produces microcracks at the inclusion/matrix interface, which leads to deterioration in mechanical properties.

Table - 4.4 : Effect of amount of cold rolling prior to annealing on the properties of the cold rolled and annealed Fe-Ni clad strip.

S.No.	%Cold rolling prior to annealing	U.T.S. in MN/m^2	% Elongation
1.	30	271	33
2.	50	272	39
3.	60	270	32
4.	70	269	30
5.	81	248	24

Table 4.5 : Mechanical properties of finished Fe-Ni clad
             strip

Fe/Ni thickness ratio in the finished strip = 5:2.

Hot-rolling thickness reduction = 86.3%

Cold rolling thickness reduction = 50%

Annealing temp.   = 700°C

  Annealing time   = 90 min. in H_2

Final thickness of the strip = 0.38 mm.

UTS, MN/m^2 272

0.2 percent proof stress,   78
MN/m^2

Elongation, %   39

Young's Modulus of elasticity, 46460
MN/m^2

Strength coefficient   126
  " K. MN/m^2

Strain hardening   0.310
exponent (n)

4.9 Mechanical properties of the Fe-Ni clad strip produced under optimum condition.

From the previous discussion, it is clear that about 80% thickness reduction by hot rolling produces a fully dense Fe-Ni clad strip. Further, a cold rolling of 50% produces optimum properties in the finished cold rolled and annealed clad strip. Table   shows the mechanical properties of the finished Fe-Ni clad strip produced under optimum condition. The finished cold rolled and annealed Fe-Ni clad strip contained the nickel and iron layers in the same ratio as in the original porous strip.   Table   shows the mechanical properties of the finished iron and nickel strips prepared under similar conditions of hot and cold rolling, and annealing.

The elastic behaviour of a laminated composite under uniaxial loading within the plane of the composite is analogous to that of a uniaxial fiber - reinforced composite stressed parallel to the fibre direction, and can be readily predicted on a rule of mixture basis. Thus the effective Young's modulus of the Fe-Ni clad strip is given by

$$E = E_{Ni} \, f_{Ni} + E_{Fe} \cdot f_{Fe}$$

where, E is the Young's modulus of the clad strip

E_{Ni} and E_{Fe} are the Young's modulus of nickel and iron strip

f_{Ni} and f_{Fe} are the volume fraction of nickel and iron in the clad strip.

The predicted yield strength of laminated strip σ_y is given by

$$\sigma_y = \frac{\sigma_{y^*}}{E^*} (E_{Ni} \, f_{Ni} + E_{Fe} \cdot f_{Fe})$$

where σ_{y^*} and E^* are the yield strength and Young's modulus of the component laminae having the lowest σ_y/E ratio.

It has been found that the clad strip follows the classical work-hardening equation $= K^n$ and the value of K in the present case is given by :

$$K = K_{Ni} \, t_{Ni} + K_{Fe} \, t_{Fe}$$

where K_{Ni} and K_{Fe} are the strength coefficient of nickel and iron strip respectively, and t_{Ni} and t_{Fe} are the thickness fraction of nickel & iron in the clad strip.

On the basis of the above equations, the various properties of the Fe-Ni clad strip was calculated and are compared with the experimentally observed value in Table 4.7. It can be seen that the experimentally observed values are comparable to calculated values.

Table 4.6 : Mechanical properties of iron and nickel strips produced from respective powders under similar optimum conditions.

Hot-Rolling thickness reduction = 86.3%

Cold-Rolling thickness reduction = 50%

Annealing temp. = 700°C

Annealing time = 90 min.

Strips	0.2% yield stress MN/m^2	U.T.S., MN/m^2	% Elongation	K MN/m^2	n	E MN/m^2
Fe	91	255	36	150	0.240	48780
Ni	62.5	325	40	83	0.486	40000

Table 4.7 : Comparison of the experimentally observed and calculated mechanical properties of Fe-Ni 15:2 clad strip.

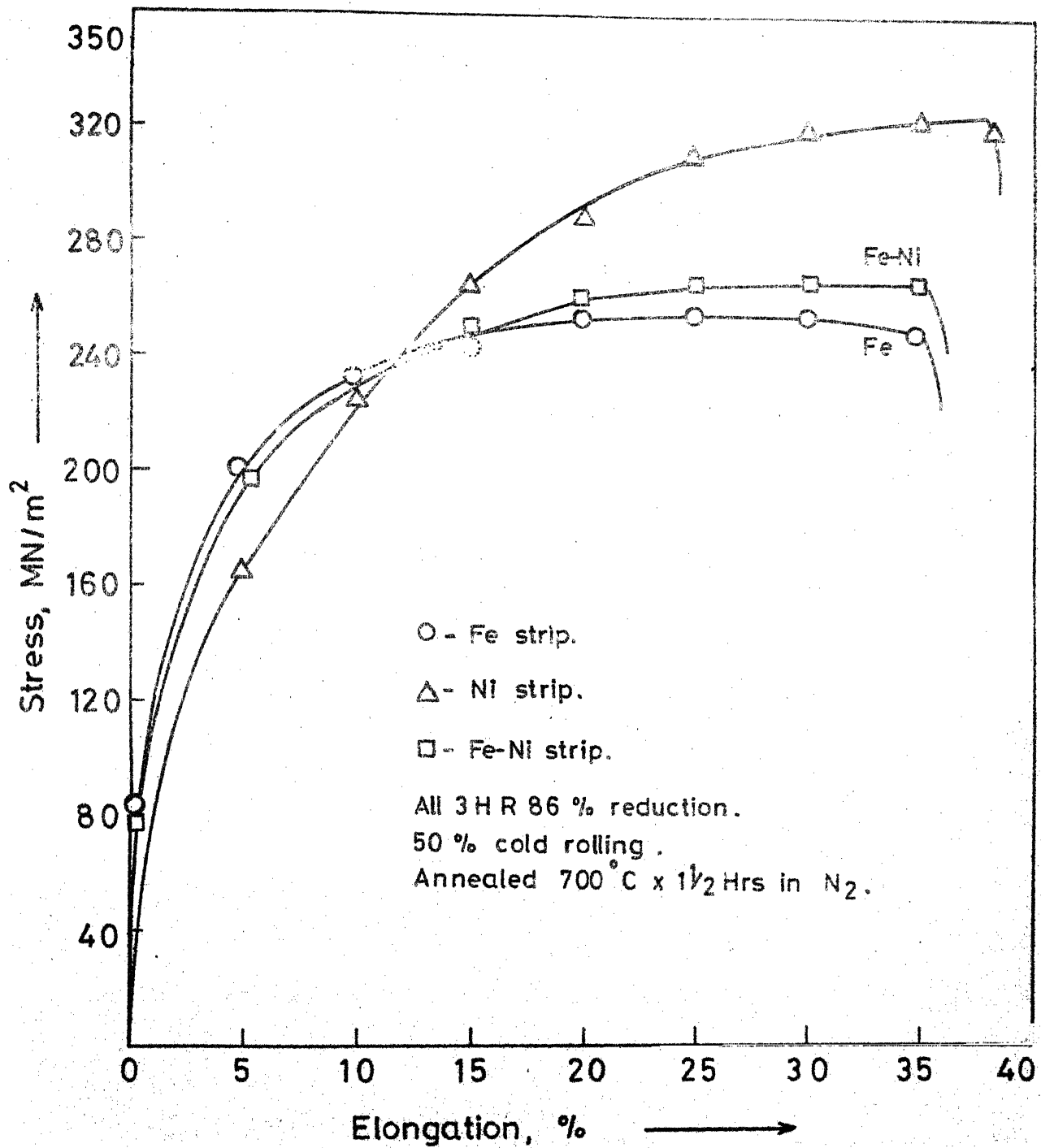| Properties	Calculated	Experimental
Young's modulus, MN/m^2	$48780 \times \frac{5}{7} + 40000 \times \frac{2}{7}$ $= 46270$	46460
Yield strength, MN/m^2	$\frac{62.5}{40000} (48780 \times \frac{5}{7} + 40000 \times \frac{2}{7})$ $= 72.30$	78
K, MN/m^2	$150 \times \frac{5}{7} + 83 \times \frac{2}{7}$ $= 130.8$	126

Fig: 4.12   Stress elongation curve of strips .

All 3HR 86% reduction.
50% Cold rolling.
Annealed 700 C X $1\frac{1}{2}$Hrs in N_2.

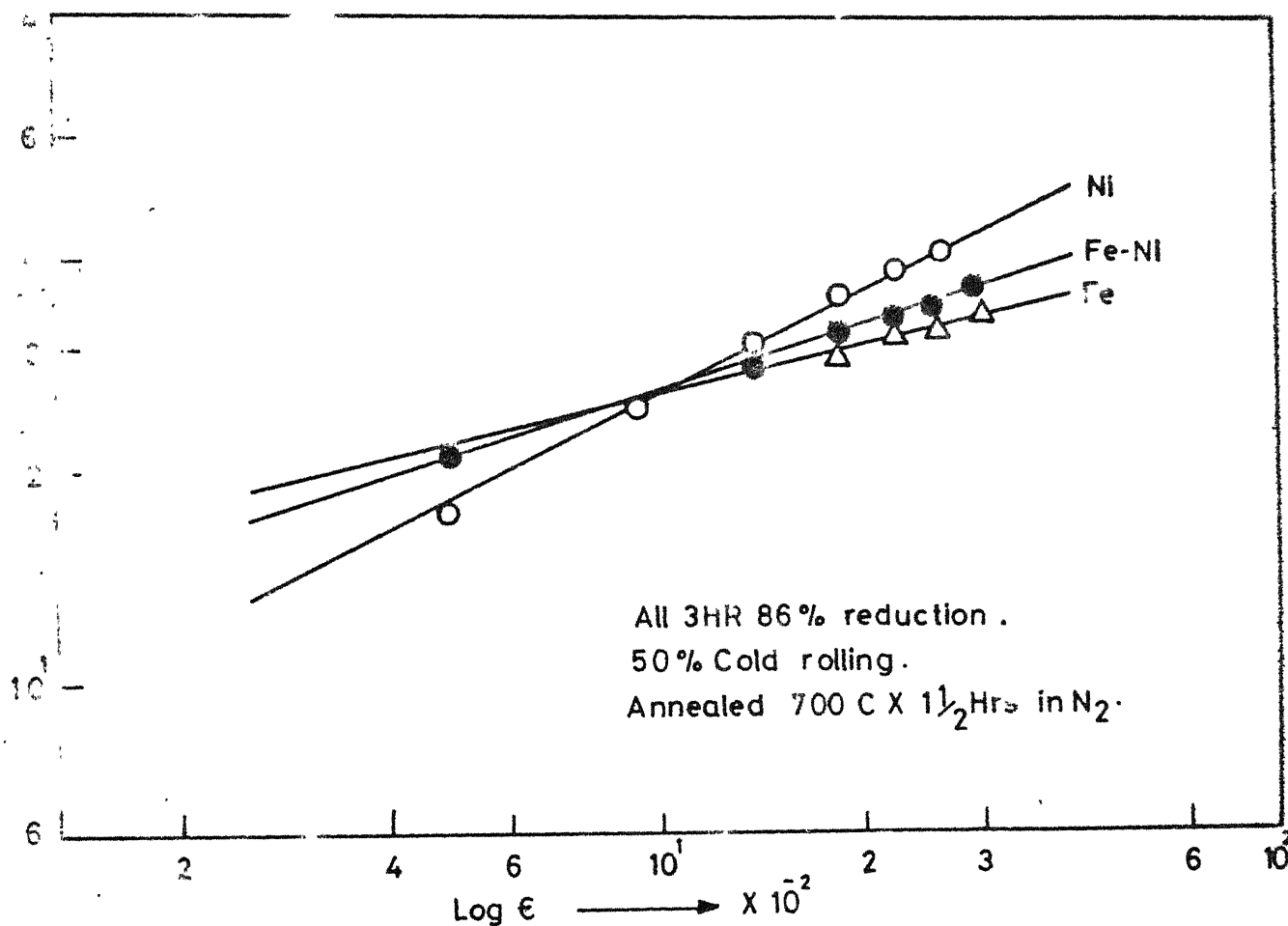Log ϵ ⟶ X 10^2

Fig. 4.13 True stress-strain curve of Fe-strip, Ni-strip and Fe-Ni strip.

CHAPTER - 5

CONCLUSION

1.   A Powder Metallurgy route for making Fe-Ni clad strip has been proposed, which consists of preparing a homogeneous and free flowing slurry mixture from iron/steel powder and a binder. The iron/steel powder slurry is cast into a strip form and dried, subsequently nickel powder slurry is deposited on to it which after drying resulted into a porous "green" Fe-Ni clad strip. It is sintered at a suitable temperature under protective atmosphere, followed by hot rolling in a single pass to full density. The fully dense Fe-Ni clad strip is then cold rolled and annealed to produce the finished strip.

2.   It is possible to sinter "green" Fe-Ni clad strip without forming any surface crack and delamination by the judicious control of the relative thickness of iron and nickel layers, rate of heating and sintering temperature.

3.   From the data obtained in the present investigations, it is clear that for iron layer thickness of 5 mm and 10 mm a nickel layer thickness of 1 mm was found to be necessary to prevent surface crack during sintering.

4.   The sintered Fe-Ni clad strip which has 60% apparent porosity can be successfully hot rolled to full density in a single pass under protective atmosphere. This clearly demonstrates that the sintered clad strip has sufficient strength to withstand stresses and strains involved in the hot rolling.

5. A thickness deformation of about 80% by hot rolling in a single pass at 1150°C produces a fully dense Fe-Ni clad strip.

6. In the initial stages of hot rolling, the physical movement of the powder particle in the clad strip is in the thickness direction without any lengthening of the strip. In the later stages of hot rolling viz. beyond 40% thickness deformation, the reduction in strip thickness was accompanied with the simultaneous lengthening of the strip. This resulted in the plastic deformation of the individual powder particles.

7. It is possible to produce fully dense hot rolled and annealed Fe-Ni clad strip having a tensile strength of 286 MN/m^2 coupled with an elongation of 32%.

8. The fully dense hot rolled and annealed Fe-Ni clad strip can be cold rolled up to 80% thickness reduction without any intermediate annealing.

9. From the point of view of mechanical properties achieved in the final cold rolled and annealed strip, the optimum amount of thickness reduction by cold rolling has been found to be about 50%. A thickness reduction of 50% by cold rolling to a fully dense hot rolled Fe-Ni clad strip, followed by annealing at 700°C for 90 mih. in H_2 atmosphere produces a tensile strength of 272 MN/m^2 and elongation of 39% in the final strip.

10. The various mechanical properties, such as Young's modulus, yield strength and strength coefficient of the Fe-Ni clad strip obtained experimentally compares very well with those obtained from the "mixture rule" for the laminated composite material.

SUGGESTIONS FOR FUTURE INVESTIGATIONS

1. Densification of sintered clad strip by repeated cold rolling-annealing cycle should be investigated.

2. Tri-metallic strip may also be tried for making clad strip.

3. Other combinations may also be tried for making clad strip like, steel-copper, steel-stainless steel etc.

REFERENCES

1. Hawkins R. and Wright J.C. - T. Inst. Metal 99,357-371 (1971).

2. Bluhm J.I. (1961) Proc. ASTM 61.

3. Embury J.D., Petch, N.S. Writh A.E. and Wright E.S. - Trans. TMS AIME 245-2529-2536 (1967).

4. Leichter H.L. (1966), J. Spacecraft 3 No. 7, 113.

5. Almonel E.A. (1968) - Interface in composites ASTM STP-452.

6. Kenneth G. Kreider - Composite materials Vol. 4, P.77.

7. Pickard G. and Primmer P.F., Associated Lead Manufacturs Ltd. Reprinted from 'Sheet Metal Industries'; Jan. 1974.

8. Brown R.L. (1969) - Composite Engineering laminates, Capt-11 MIT Press, Cambridge Massachussets

9. Brown, R.N. (1965) - Composite Engg. laminates M.I.T. Press Capt-11.

10. Kenith G. Kreider - Metallic Matrix Composite Material Vol.IV page-94.

11. Kenneth G. Kreider - Metallic Matrix Composite Vol. IV Page 81 by the permission of Texas Instrument Inc.

12. Anctil A.A. and Kula E.B. (1969) - J. Iron Steel Inst. 207, 1319-1323.

13. Kenneth G. Kreider - M-tallic Matrix Composite Vol. IV page-80. by the permission of Army Materials and Mechanics Research Centre.

14. Lisson D.N. Copper metal bearings symposium, Melbourne October, 1969.

15. Kura J.G. - Materials Engineering, Vol. 80, No.5, Oct. 1974.

16. Blickensderfer R. - Reports of Investigation 8481.
    United States Dept. of the Interior, Bureau of Mines.

17. Dube, R...., Private communication

18. Pickard, G. and Rimmer, P.F. (Associated Lead Manufacturers Ltd.
    Steel Metal Industries, Jan. 1974.

19. Arrowsmith, J.N. and Caskie, I.M. Roll Cladding of Low Alloy
    and Mild Steel Plates., British Steel Corporation - 1974.

20. Pickard, G. and Rimmber, P.F. Cladding of Metals to iron by
    vacuum rolling. Investigation Report - 8481.

21. Singer, A.R.E., Metals and Materials, 1970, 4 (6) 246-250, 257.
    Singer, A.R.E., J. Inst.Metals, 1972-100, 185-190.

22. Dube R.K. - Private communication.

23. Katrus O.A. and Vinogradov - Poroshko Metallurgia
    No. 8 (80) August - 1969.

24. Katrus, O.A. and Vinogradov Poroshko Metallurgia.
    No. 8 (80), pp. 31-33, Aug. 1969.

25. Katrus, O.A. Sov. Powder Met. and Metals Ceramics,
    163 (7) 1976, 113.

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